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Appendix O – Revised Limnology Study

McArthur River Mine open cut: 3D Hydrodynamic Modelling for a Mine Pit Lake System

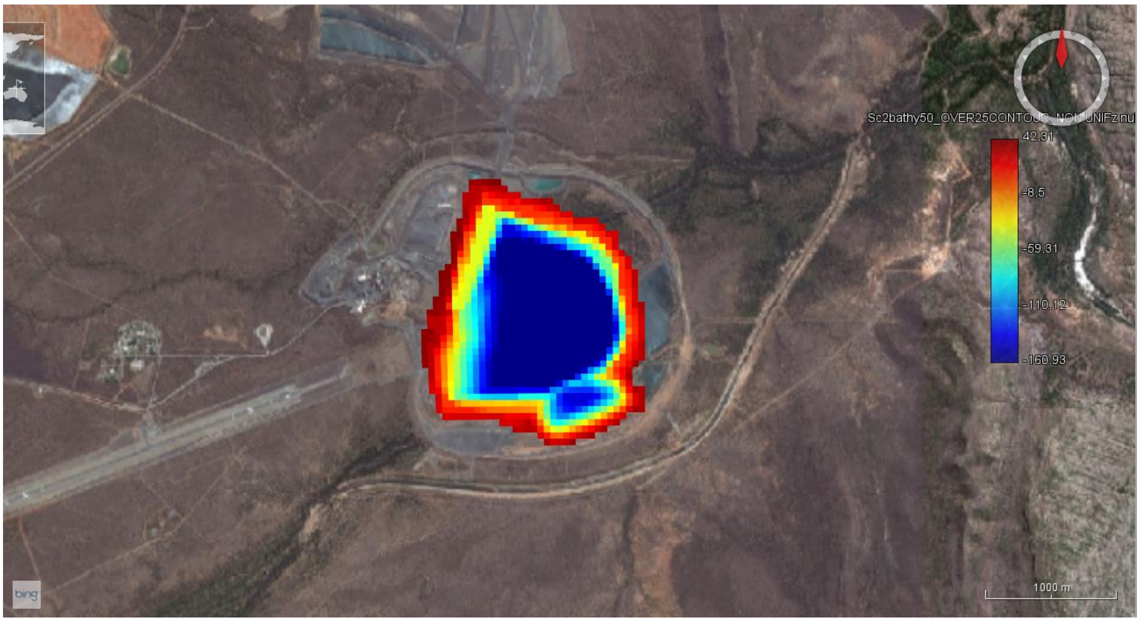

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Image on cover page: ELCOM bathymetry overlaid on Bing image in ARMS.

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Glossary of Acronyms

AHD:	Australian Height Datum: reference datum for elevation, measured in metres
ARI:	Annual Return Interval
AREMI:	Australian Renewable Energy Mapping Infrastructure
BoM:	Bureau of Meteorology
CoC:	Contaminant of Concern
EC:	Electrical Conductivity (corrected to 25°C)
GHI:	Global Horizontal Irradiance
KCB:	Klohn Crippen Berger Pty. Ltd.
NIR:	Near Infrared Radiation
PAR:	Photosynthetic Active Radiation
RPAF:	Reactive Potential Acid Forming
TWS:	Tropical Water Solutions Pty. Ltd.
MRM:	McArthur River Mine
NT:	Northern Territory
SEA:	System Engineer Australia Pty. Ltd.
UVA, UVB:	Ultraviolet A and B Radiation
WRM:	WRM Water and Environment Pty. Ltd.

Glossary of Terms

Australian Height Datum (AHD):	Reference datum for elevation, measured in metres.
Anoxic water:	Water with zero oxygen concentration.
Annual Return Interval:	The Annual Return Interval is an estimate of the likelihood of an event, such as an earthquake or a flood, to occur. The theoretical return period is the inverse of the probability that the event will be exceeded in any one year (or more accurately the inverse of the expected number of occurrences in a year). For example, a 10-year flood has a 1/10 = 0.1 or 10% chance of being exceeded in any one year and a 50-year flood has a 0.02 or 2% chance of being exceeded in any one year.
Chemocline:	A chemocline is a cline caused by a strong, vertical chemistry gradient within a body of water.
Epilimnion:	The surface mixed layer, lying above the pycnocline of a stratified lake (see also Hypolimnion).
Hypolimnion:	The deep-water layer, lying below the pycnocline of a stratified lake.
Hypoxia:	The condition of water describing an oxygen demand.
Insolation	Total incoming solar radiation.
Lagrangian:	A function that describes the state of a dynamic system in terms of position coordinates and their time derivatives and that is equal to the difference between the potential energy and kinetic energy.
Limnology:	Limnology is the study of lakes covering biological, chemical, physical, geological, hydrological and other attributes.
Metalimnion	The layer of water between the upper epilimnion and the deeper hypolimnion including the thermocline and pycnocline.
Pycnocline:	The region of greatest density change in a stratified lake. In freshwater lakes, its position coincides with the thermocline. The pycnocline's central position in the water column of a lake may be mathematically described as that coinciding with the volume-corrected mean of a lake's internal buoyancy frequency.
SILO data	'SILO' stands for Scientific Information for Landowners and is a matrix of meteorological information held by several Australian Government Departments and Agencies.
Stratification:	The thermal stratification of lakes refers to a change in the temperature at different depths in the lake, and is due to the change in water's density with temperature. Lake stratification is the separation into three layers: Epilimnion, Metalimnion or Thermocline and Hypolimnion.
Thermocline:	The region of greatest temperature change in a stratified lake. In freshwater lakes, its position coincides with the pycnocline.

1. INTRODUCTION

The purpose of this study is to model the hydrodynamic behaviour of the McArthur River Mine (MRM) mine pit lake including its initial filling, isolation and a period of time after the cessation of mining. Hydrodynamic modelling was undertaken to inform the associated mine pit lake water quality modelling by providing:

- An indication of the rate of development of stratification for a range of flow conditions;
- An indication of the degree of mixing between surface flows and the deeper regions of the mine pit lake;
- An indication of the depth of the pycnocline/thermocline for each of the flow conditions;
- Based on the preceding point, the depths to which oxygen could be transported as a result of water flow and seasonal vertical turbulence transport. (Oxygen transport by diffusion is modelled in the mine pit lake water quality model.)
- To provide information on the potential for resuspension of sediment solids from the bed of the mine pit lake.

MRM is located approximately 90 kilometres inland in the south-west region of the Gulf of Carpentaria. This report and the supporting model outputs are based on three scenarios following filling and isolation of the MRM pit lake and include:

1. Flow Through: Flows from the McArthur River being allowed to travel through the mine pit lake entering through an upstream inflow levee and re-joining the river through a downstream outflow levee. This may be described as a ‘flow through’ scenario.

2. Back Flow: Flows from the McArthur River enter the mine pit lake via backflow that enters the lake through a levee located on its (original) downstream side. An upstream levee prevents flows from the original upstream McArthur River directly entering the lake. This may be described as a ‘back flow’ scenario.

3. Extreme event: Flows from the McArthur River enter the mine pit lake via backflow that enters the mine pit lake in its downstream channel with an upstream levee that prevents flows from the upstream McArthur River directly entering the lake. Soon after this backflow starts the mine pit lake is impacted simultaneously by a cyclone and a 1:1000-year flood event (1000-year ARI). As result of these combined extreme events, both the upstream and downstream levees fail. These failures cause a resumption of a ‘flow through’ scenario associated with the levee failures and an extreme flood event through the mine pit lake. This flow through continues for several weeks until both levees are repaired.

The Model simulations were run for 20 years starting on 1 October 2047 extending to 30 September 2067. Following a period of pumped filling and isolation, inflows from McArthur River begin on 17 March 2058. The detailed sequence of events for each of the above scenarios vary and are explained individually in their respective sections later in this report.

For all scenarios a tropical cyclone was simulated to impact the pit lake on 23 March 2058. The meteorological simulation is based on data obtained from Cyclone Kathy which impacted the town of Borroloola located some 45 kilometres inland in the south-western region of the Gulf of Carpentaria on 23 March 1984. This was included in the simulations in order to evaluate the likely impact of an extreme event on the hydrodynamics of the mine pit lake. This event is further detailed in Section 2.1.4.

Appendix 1 shows a transverse vertical view of the potential for accumulation of Contaminants of Concern (CoC) in the mine pit lake over the period of modelling from 1947 to 1967.

2. MATERIAL AND METHODS

A three-dimensional hydrodynamic model was built for the McArthur River final open cut void based on the planned geometry at closure. The focus of this modelling exercise is the temporal and spatial behaviour of temperature and density within the water body. This is accompanied by the use of proxy tracers of major inflows and outflows to provide information and understanding of dilution and concentration of conservative water quality parameters in the mine pit lake over time.

The numerical model tool chosen was AEM3D. AEM3D is owned by Hydronumerics Pty. Ltd. and applies three dimensional hydrodynamic and thermodynamic models to simulate the temporal behaviour of stratifying water bodies with environmental forces. The hydrodynamic simulation method solves the unsteady, viscous Navier-Stokes equations for incompressible flow using the hydrostatic assumption for pressure (Hodges B.R. & Dallimore C, 2016). AEM3D is a refinement of the original ELCOM (Estuary, Lake and Coastal Ocean Model) which was developed by the Centre for Water Research (CWR) at the University of Western Australia. Both AEM3D and ELCOM have been applied globally in numerous and varied aquatic and coastal environments.

2.1 Input data

The ideal meteorological data to force hydrodynamics is in time steps of one hour or less. The input data used to force AEM3D are summarised in Table 1.

Table 1: Summary of the data used to force AEM3D.

Location	Data type	Time Step	Data Source	Period	Units
Bathymetry					
McArthur River Mine	x, y, z	-	Glencore	-	m (AHD)
Meteorological Data					
McArthur River Airport Station	Air Temperature	9 am and 3 pm	BOM	1976-1996	°C
McArthur River Airport Station	Rainfall	Daily	BOM	1976-1996	m
McArthur River Airport Station	Wind Speed	9 am and 3 pm	BOM	1976-1996	m/s
Cyclone Modelled data	Wind Speed	30 min average	SEA	March 1984	m/s
McArthur River Airport Station	Wind Direction	9 am and 3 pm	BOM	1976-1996	degrees true north
Cyclone Modelled data	Wind Direction	30 min average	SEA	March 1984	degrees true north
McArthur River Airport Station	Relative Humidity	9 am and 3 pm	BOM	1976-1996	-
McArthur River Airport Station	Cloud Cover	9 am and 3 pm	BOM	1976-1996	-

Darwin Airport Station	GHI	1 hour average	AREMI	2014-2015 looped	Wm^{-2}
Boundary Conditions					
MRM modelled surface water	Local catchment	Daily	WRM	1950-1970	m^3s^{-1}
MRM modelled surface water	McArthur River flow	Daily	WRM	1960-1970	m^3s^{-1}

2.1.1 Configuration and initial conditions

The summary configuration setup for AEM3D is shown below in Table 2.

Table 2: Summary of AEM3D configuration for the mine pit lake

Description	Setting
Simulation period	1 October 2047 to 30 September 2067
Computational time step*	60 seconds
Albedo	0.08
PAR extinction coefficient	0.4
NIR extinction coefficient	1.0
UVA extinction coefficient	1.0
UVB extinction coefficient	1.0
Initial water level	-167.39m AHD (dry pit)
Initial salinity	0.33 PSU
McArthur River upstream inflow tracer	1
McArthur River downstream inflow tracer	1

*The computational time step was modified for the 'extreme event' scenario. See Section 3.4.

2.1.2 Tracers

Proxy tracers are employed in the modelling outputs to provide information on the evolution of source water after it enters the lake over the modelled time period. These tracers provide information on the source of water entering the mine pit lake in relation to the fate of these waters in the profile of the lake. All tropical lakes, including mine pit lakes, exhibit strong variations in seasonal stratification due to seasonal changes in the vertical density structure within the profile due to a wide range of seasonal meteorological factors (Boland & Padovan, 2002; Boland & Imberger, 1994; Lewis, 1996). Once water from a particular source enters the water body it will be distributed into the water column in response to its neutral buoyancy depth in the lake's profile at the time of the inflow (i.e. the depth at which inflow density is the same as that density in the profile of the mine pit lake). This is often called the 'intrusion depth'. Once the intrusion depth is reached the inflows will remain largely confined to this depth but subject to any subsequent vertical forcing in the water column that may cause transport of these waters into the deeper regions of the lake. This will include seasonal deepening of the thermocline/pycnocline associated with winter cooling, steady state diffusion and shear forcing between different layers of a stratified lake. The transport of inflow waters into the deeper regions of a lake profile can thus occur even under conditions of strong stratification existing much higher in the water column. For example, a partial mixing event may cause the thermocline of a lake to deepen from (say) 20 metres depth to 50 metres depth. This may cause disruption of inflow waters that had, prior to this partial mixing, settled around a previous intrusion depth of (say) 30 metres depth. These waters may, due to this partial mixing be redistributed in a region between 30 and 50 metres depth. Subsequent to the partial mixing event, strong stratification may re-establish at (say) 15 metres depth. Notwithstanding this, the inflow waters that have been 'pushed' and distributed into the deeper parts of the water column will remain there but still be subject to factors such as steady state diffusion that may distribute them even deeper into the water column. In this sense, it is important to clearly distinguish between the longer-term fate of inflow tracers in the water column, and seasonal changes in stratification and mixing in the water column.

Water retention time ('water age') profiles in the mine pit lake are also modelled for each scenario and are subject to the same principles discussed above for tracers.

As noted above the model was run for 20 years, starting on 1 October 2047 and continuing until 30 September 2067. The simulation includes two tracers, as noted below:

Tracer 1: Upstream McArthur River inflow water entering the mine pit lake

Tracer 2: Downstream inflow from the McArthur River backflow channel entering the mine pit lake

Both tracers are set to the nominal value of 1 (no units) so that a signal of 0.4 in any tracer graphic would mean that 40% of the water in that graph would have been sourced from its assigned source region. It should be emphasised that these tracers are 'mass conservative' so that under some (unusual) circumstances, they can exceed 1 (i.e. >100%). Detailed explanations of these tracers are included in respective sections of this report describing the three different flow scenarios in the mine pit lake.

2.1.3 Bathymetry

Bathymetric data was provided by Glencore in the form of a 'x y z' topography file of the proposed open cut contours at closure. The provided topography was modified to define the surface of the tailings layer at a maximum height of approximately -167.94 m AHD, giving a maximum water depth of 187.94 m. A three-dimensional computational domain was setup with the above-mentioned bathymetric data set. The grid has a lateral resolution of 100 x 100 m and a non-uniform vertical resolution that varies progressively with depth, forming a total of 65 layers (See Figure 1).

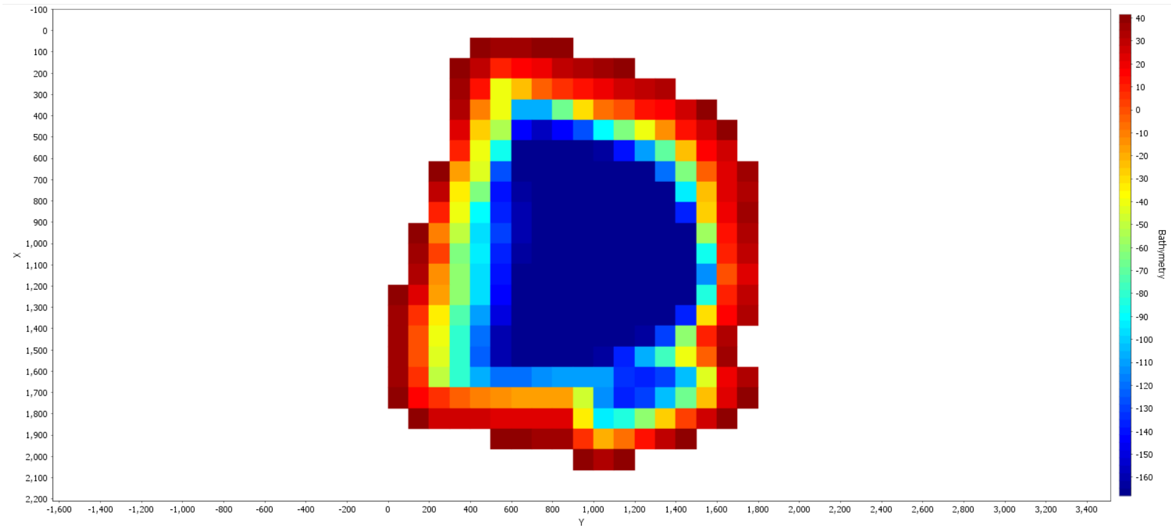


Figure 1: Final Bathymetry of mine pit lake. Horizontal resolution is 100 m * 100 m. Legend in m (AHD).

2.1.4 Meteorological data

SILO weather/climate data were not used to structure the meteorological data. One of the major reasons was that the data frequency provided is daily and therefore insufficient to simulate diurnal variations. Additionally, the usable variables available are limited to rainfall, solar radiation and relative humidity. Air temperature, wind speed, wind direction, cloud cover, and additional meteorological data had to be extracted from BoM data sets, as they were not available in SILO. Thus, it was concluded that a combination of SILO and BoM would likely cause inconsistency in the meteorological input data.

The closest meteorological station to the study area is McArthur River Airport Station (BoM station 014704) where the following meteorological parameters were extracted: air temperature, cloud cover, humidity fraction, wind speed, wind direction and rainfall for the period 1976 to 1996. All variables were available in a frequency of two measurements per day (9am and 3pm) except for rainfall which had been recorded in the 24 hours before 9 am. Global Horizontal Irradiance (GHI) was obtained from Darwin Airport Station (014015), as station 014704 did not have suitable GHI data to force AEM3D. Measured solar data has been reported only from 2003. Since this data is known to have several large gaps, a decision was made to extract and process years 2013-2014 and loop it to cover the model run.

On 23 March 1984, Tropical Cyclone Kathy passed over Borroloola. Data associated with this event was used to simulate an extreme weather event in the modelled data. Higher resolution modelled wind data of 30-minute time steps was inserted into the twice daily BoM data to better represent the atmospheric situation from 21/03/1984 to 23/03/1984, when the cyclone actually passed over the area. This cyclone model data was provided by System Engineer Australia Pty. Ltd. In order to maximise the extremity of the event, wind data used to represent the cyclone was that calculated for Borroloola (approximately 45 kilometres from the coast), but used at the MRM site some 90 km inland. In this way, the simulation represents Tropical Cyclone Kathy occurring directly over the surface of the mine pit lake.

The cyclone associated input data described above is displayed in Figure 2 with the dates converted to include the modelled period, 2047-2067. After converting these dates, Cyclone Kathy impacts the mine pit lake on 23 March 2058. This is easily identifiable by the approx. 29 m/s peak shown in the wind data on the 23 March 2058 (See Figure 2).

The thermal profile of the lake during the filling and isolation period developed based on the meteorological inputs to AEM3D.

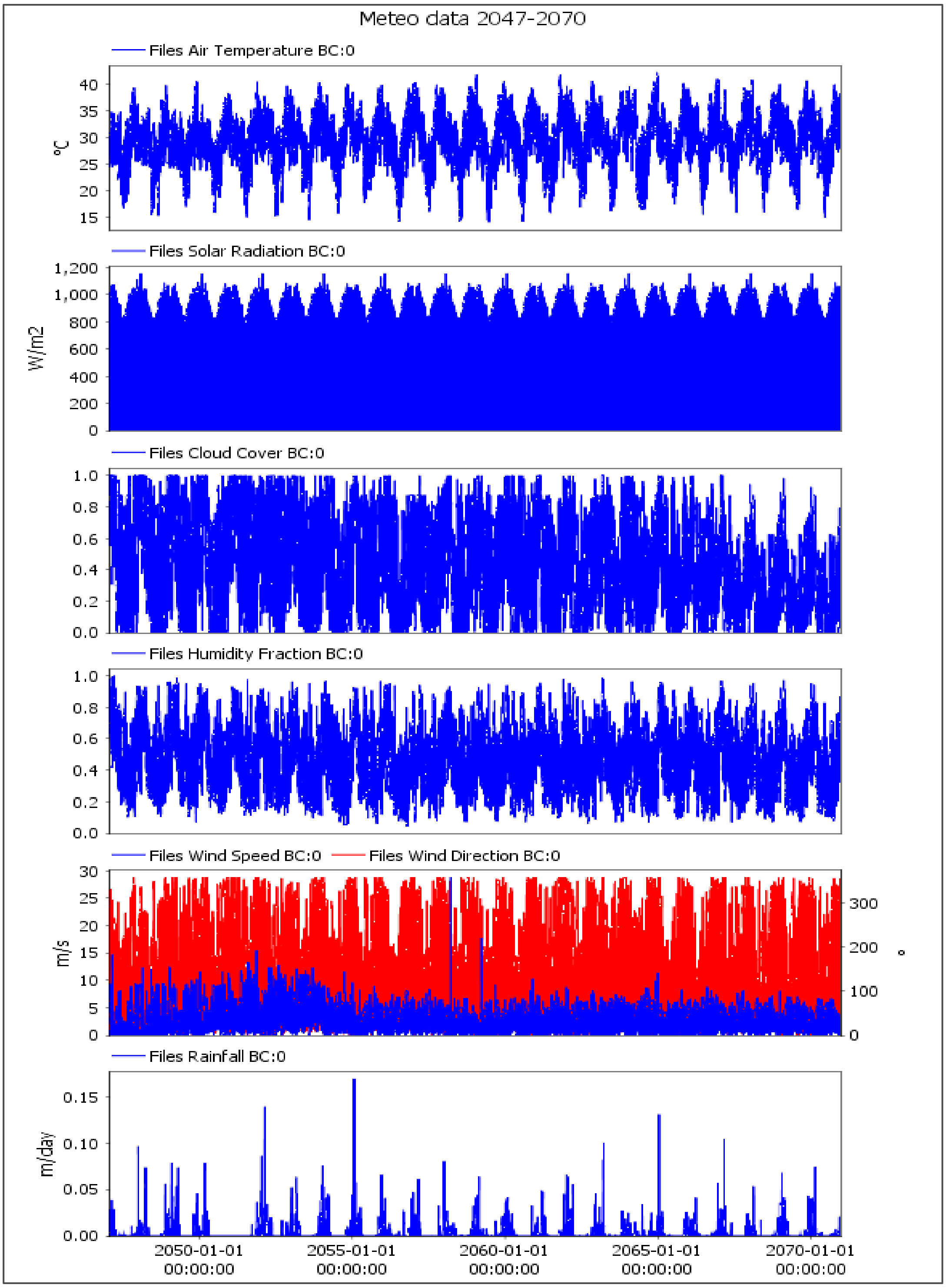


Figure 2: Meteorological data for the MRM mine pit lake including the modelled period from October 1, 2047 to September 30, 2067 used as inputs the for AEM3D model. From top to bottom: Air Temperature, Solar Radiation, Cloud Cover, Humidity Fraction, Wind Speed, Wind Direction and Rainfall.

2.1.5 Boundary conditions

Flow forces consisted of modelled flow rate data provided by WRM Water and Environment Pty. Ltd. and cover the modelled period from 1 October 2047 to 30 September 2067.

Inflow water temperature was estimated from air temperature data obtained from the BoM. Water temperature is expected to be on average lower and less variable than air temperature (due to the high specific heat of water). Based on this, a five-day moving average was applied to air temperature records with the purpose of smoothing and lowering the input data for water temperature.

The Electrical Conductivity (EC_{25}) of all inflows from the McArthur River are less than 500 µS/cm (WRM, 2017). Even during the pumped filling phase, the maximum EC was <1500 µS/cm. These values are very low and would contribute very little to the density differentials in the mine pit lake's water density profile compared to that due to temperature differences (See *CRC Handbook of Chemistry and Physics*, 98th edition, 2017). Thus, inflow salinity was defined as a constant at 0.33 PSU, based on an average calculated on McArthur River water quality data obtained from the NT Government website for the MRM Upstream Gauging Station. In MRM mine pit lake, profile density variability is strongly dominated by temperature differences with very little contribution from salinity. Thus, assuming a constant salinity in the inflowing water is reasonable.

Inflow rates and volumes vary with each of the scenarios and are detailed later for each of the modelled scenarios. While filling volumes and local catchment flows are included in the output flow graphs, their respective contributions to the overall flow volumes entering the mine pit lake are very much less than the river flows.

Figure 3 below shows a schematic of the dominant flows for all of the scenarios modelled and the terms used in this report to describe each of these flows.

As noted in Section 2.1.2, two tracers are included for upstream and downstream river inflows, each with an arbitrary concentration of 1 (no units). This gives an indication of the fraction of water in the void that comes from each of these different sources.

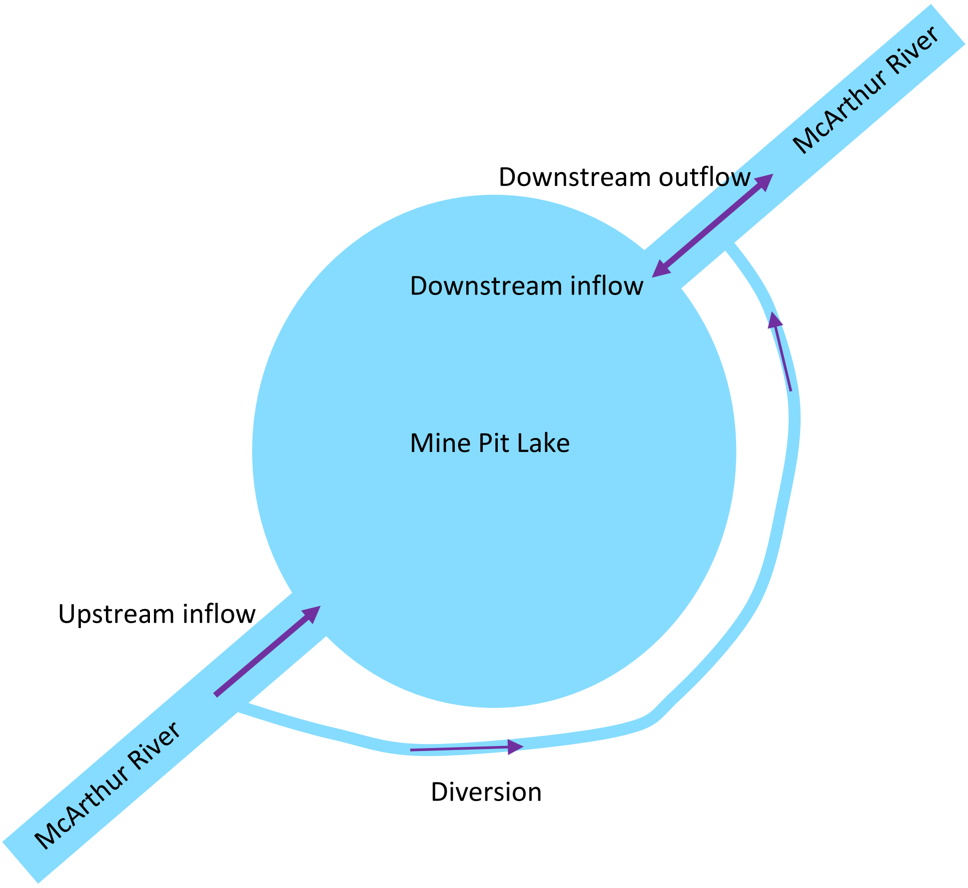


Figure 3: Schematic diagram of modelled flows entering and leaving the mine pit lake

3. Model Outputs

3.1 Overview

The variables selected as output of the 3D AEM3D configuration are:

- Water temperature;
- Upstream McArthur River inflow tracer;
- Downstream McArthur River inflow tracer (i.e. via backflow channel); and
- Water retention time through the mine pit lake profile.

Figure 4 shows the location of the 1D (grey dot) output location in the AEM3D bathymetry map.

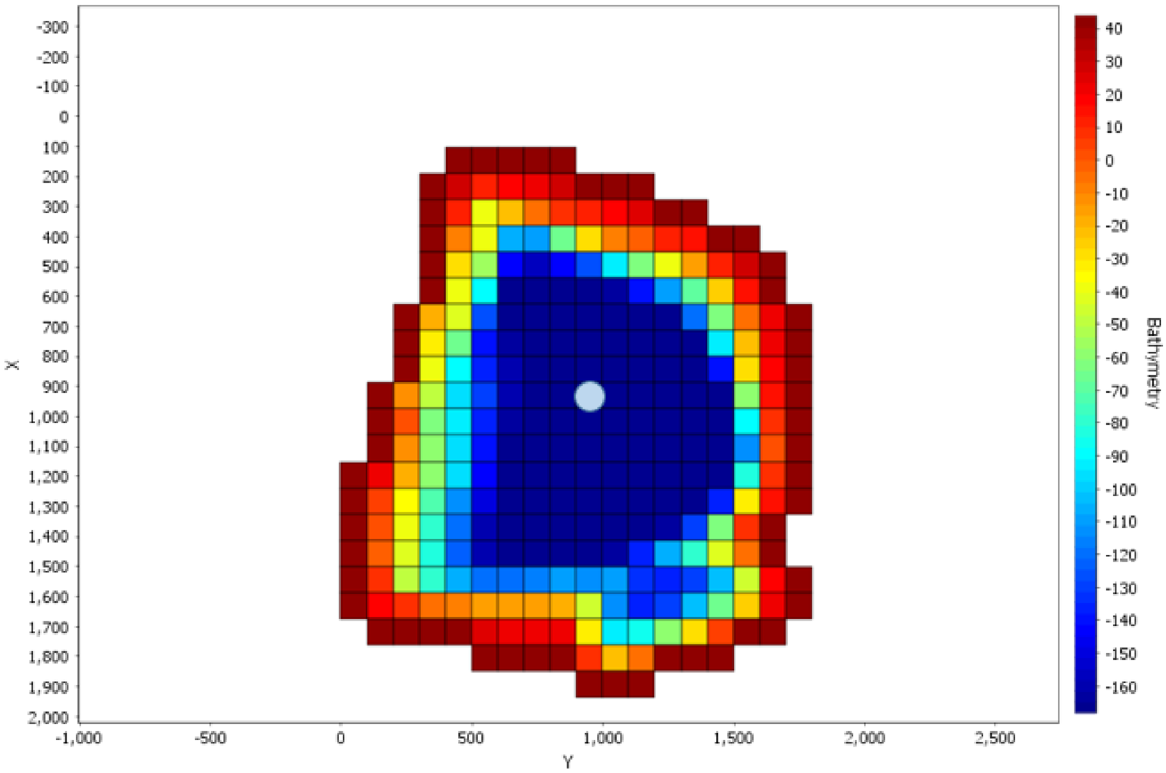


Figure 4: Bathymetry showing 1D output location (dot in centre of map) exported as AEM3D results. Bathymetry legend in m (AHD).

3.2 Outputs for flow through scenario

The flow through scenario involves the construction of two levees, one on the upstream entry of the McArthur River into the mine pit lake and another on the outlet of the mine pit lake flowing to the downstream McArthur River. These are constructed at 25m AHD and 20m AHD respectively. On 17 March 2058 these levees are opened to allow flow from the McArthur River into and out of the mine pit lake concurrent with flows in the river being greater than 25m AHD. The diversion channel is maintained so that flows between 20m AHD and 25m AHD will also flow into the mine pit lake from the downstream levee via the channel constructed to the downstream portion of the diversion channel (See Figure 3). On 23 March 2058, 6 days after the levees are opened, a cyclone as described in Section 2.1.4 above, directly impacts the lake. The WRM modelled flow outputs of this scenario follow.

Flows for this scenario are shown in Figure 5.

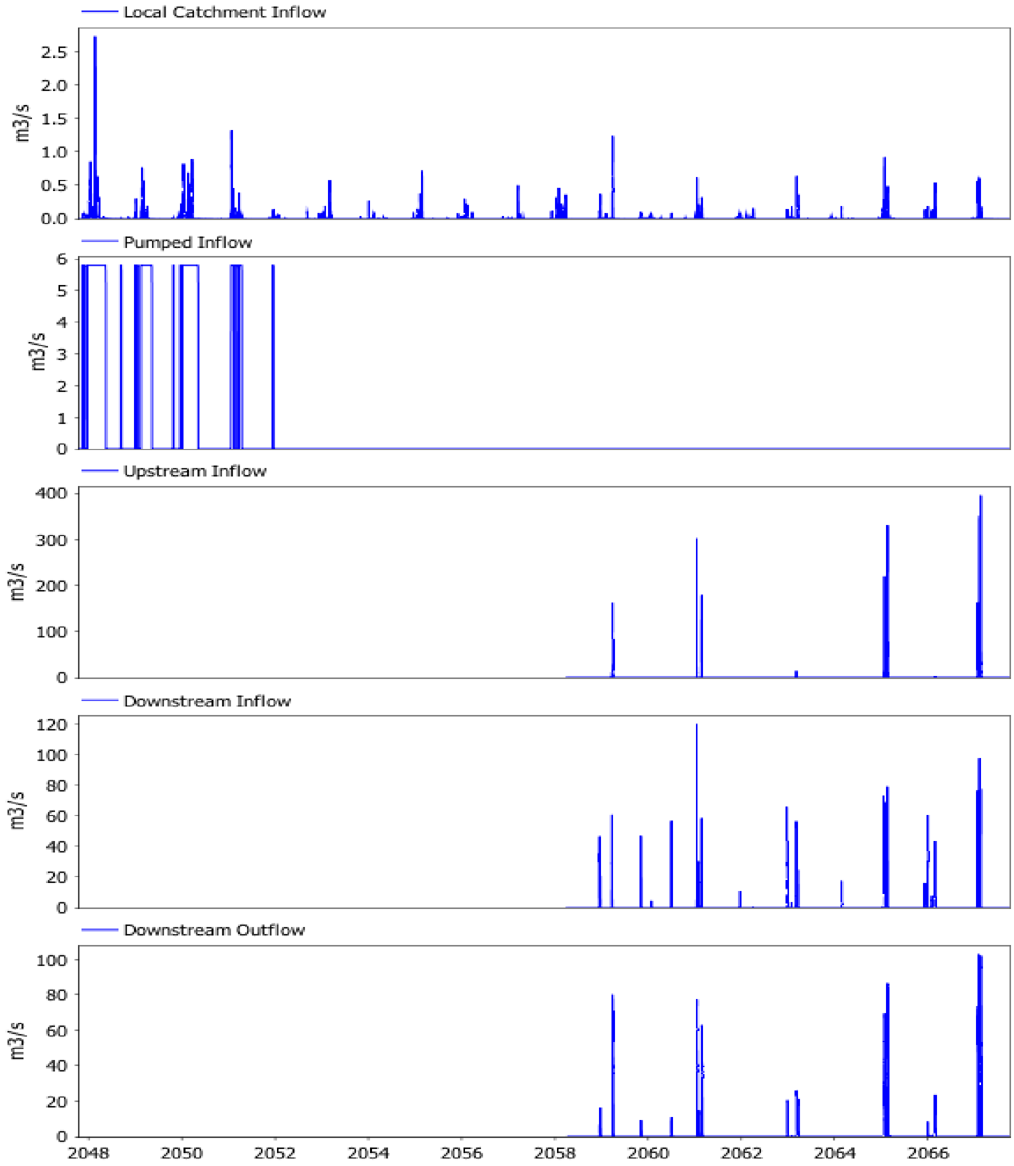


Figure 5: Flows entering and exiting the mine pit lake for a flow through scenario (WRM data).

3.2.1 Temperature profile October 2047 to September 2067 for flow through scenario

Figure 6 below shows the modelled temperature profile point in the centre of the mine pit lake (location shown in Figure 4) for the complete simulation period, 1 October 2047 to 30 September 2067.

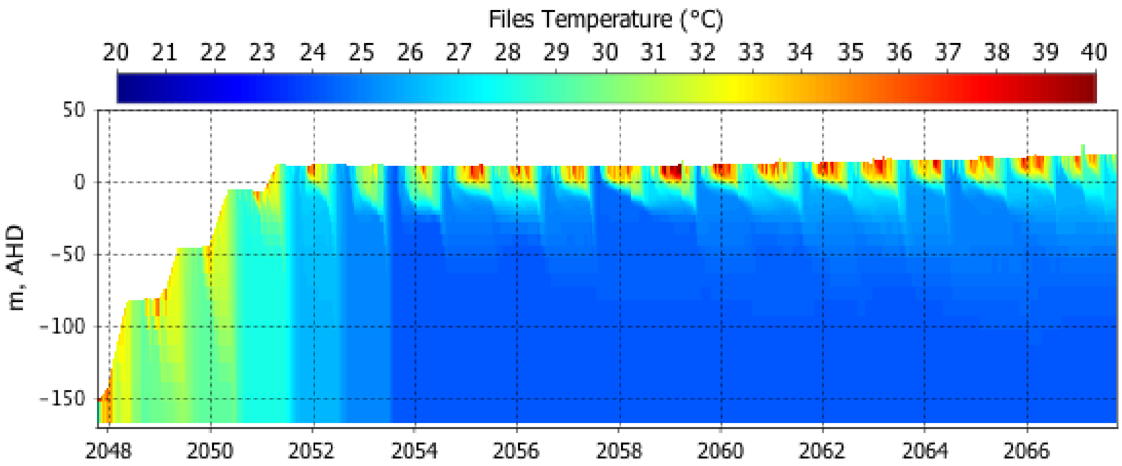
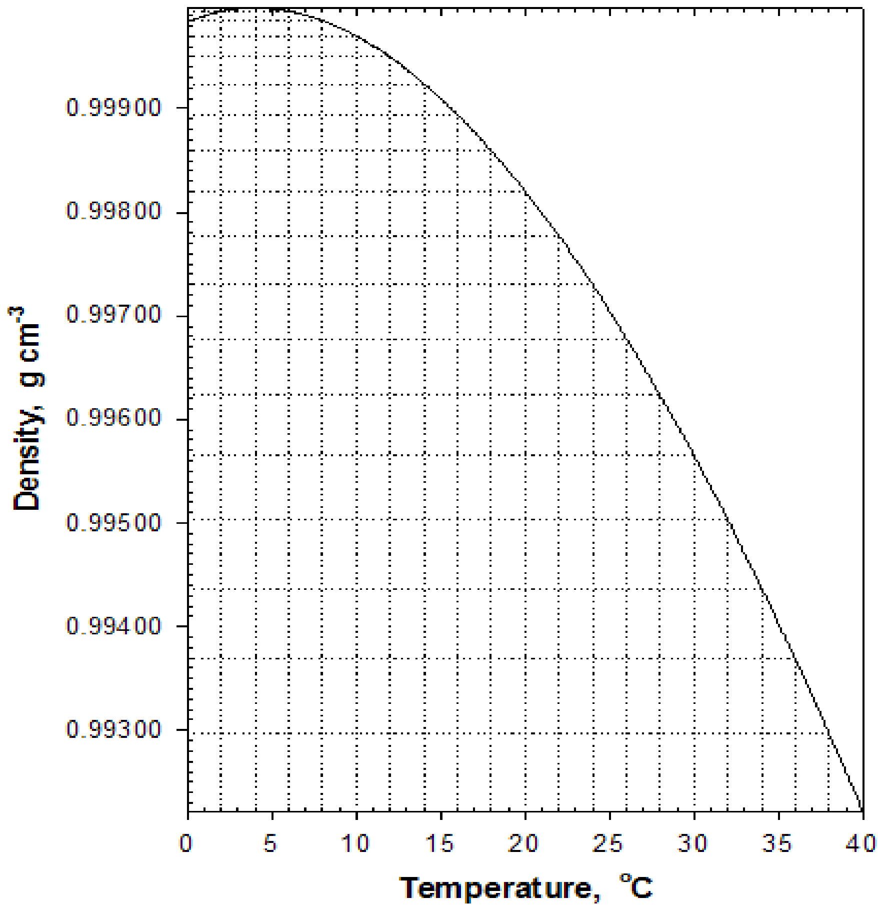


Figure 6: Modelled Temperature profile for period 1 October 2047 to 30 September 2067 for a flow through scenario.

The temperature profile seasonal structure in Figure 6 shows that a significant thermocline structure is maintained at approximately -0m to -10m AHD during summer months with seasonal winter deepening due to partial mixing extending to around -50m AHD. This winter deepening is due mainly to seasonal decreases in air temperature and insolation rates but is generally confined to the upper portion of the water column above approximately -50m AHD. The strength of this stratification is best illustrated by Figure 7 below which shows the temperature/density relationship of water. It is the strength of this vertical density variation (the 'pycnocline') that ensures that the pit lake does not completely mix at any time during the modelled flow-through period. In essence, the forcing energy is insufficient to generate enough upper water column 'work' during this period to generate strong vertical mixing below approximately -50m AHD (i.e. approximately 70m water depth).

Notwithstanding this, seasonal winter deepening will vary from year to year and toward the end of the simulation period (2060 onward) some partial mixing occurs below -50m AHD. In particular the winter of 2064 shows weak partial mixing to approximately -70m to -80m AHD. This is associated with cooler than average winter air temperatures in this year along with a longer than usual cool winter period. This will however have only a minor influence on waters above -50m AHD and will be illustrated by zooms of that period and the tracer and retention time graphs that follow.



NOTES:

Values are for pure, air-free water at 1 atmosphere pressure.

Values after Chappuis (1907) and Theisen, Scheel & Diesselhorst (1900), recalculated by P.H. Bigg, *Br. J. appl. Phys.*, 1967.

The temperature of maximum density (t_m) at different pressures (p in atmospheres) is given by:

$$t_m = 3.98 - 0.0225\,(p - 1)$$

Figure 7: The relationship of water temperature and density.

To further demonstrate the deepening referred to above, zooms of data during the winters of 2062 and 2064 are shown and compared in the below Section 3.2.2.

3.2.2 Zooms of winter meteorological data and simulated temperature profile for 2062 and 2064

Data and temperature profile simulations for the winters of 2062 and 2064 are shown below in Figure 8 and Figure 9 respectively.

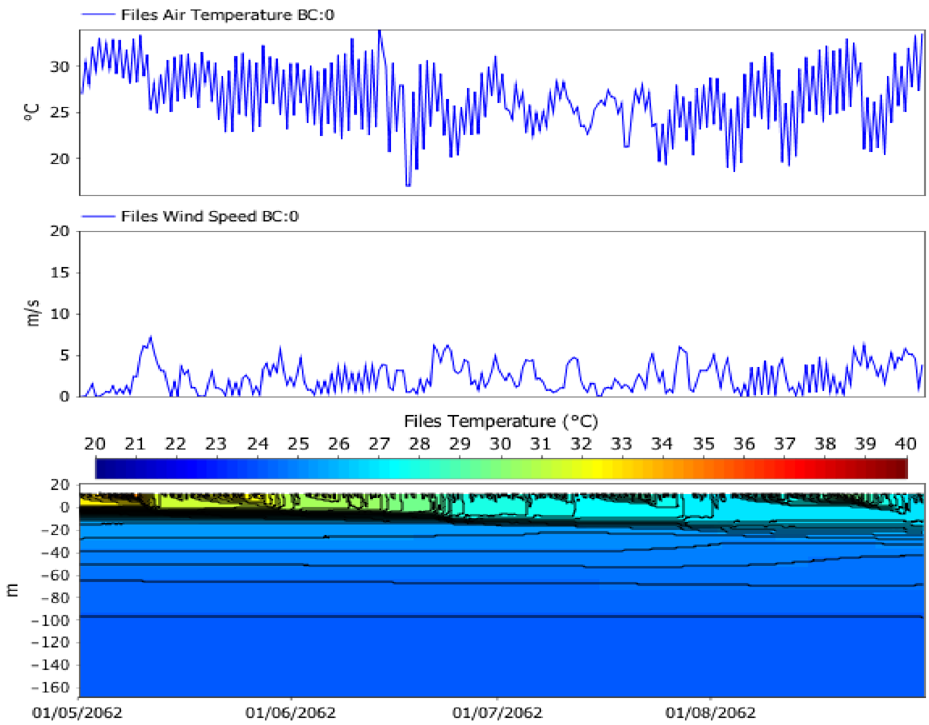


Figure 8: Air Temperature, Wind Speed and Temperature profiles for the winter of 2062

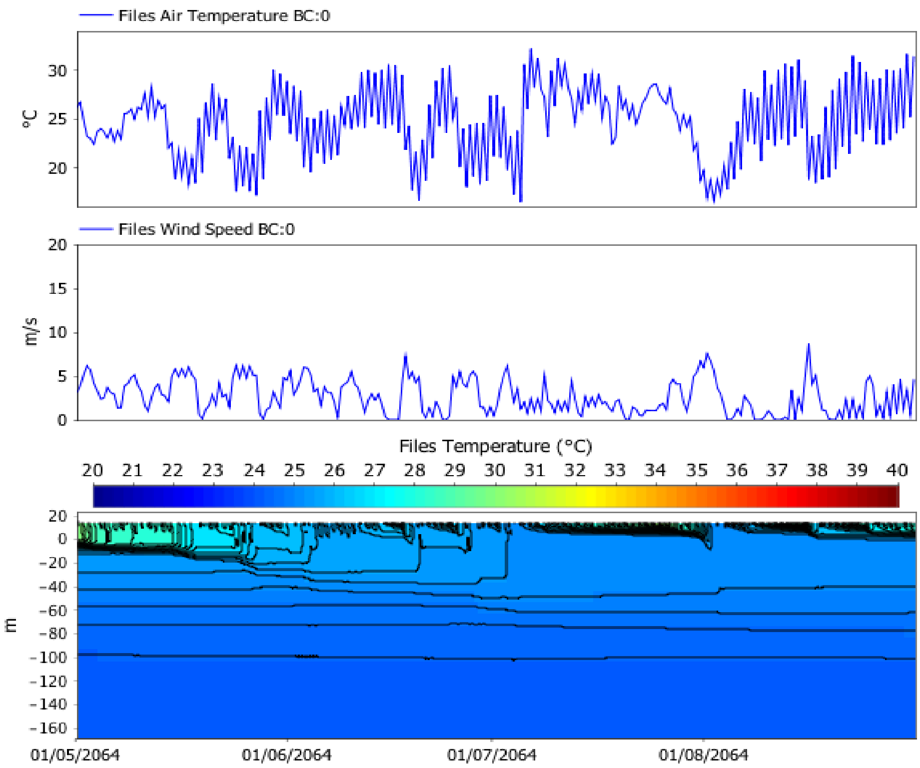


Figure 9: Air Temperature, Wind Speed and Temperature profiles for the winter of 2064

Comparing the data for 2062 (Figure 8) and 2064 (Figure 9) shows that winter average daily air temperatures vary considerably. In 2062 there was only one date in mid-June when the Temperature fell significantly below 20°C whereas in 2064 there were five (some comparatively extended) periods when this occurred. These were in mid-May, late May, the third week of June, the first week of July and finally in late July and early August. Examining peak wind for both years shows that the winter of 2064 showed higher peaks that those in 2062. Thus, the thermal profiles in these respective years vary markedly.

The bottom panel of Figure 8 andFigure 9 shows respectively the evolution of the thermocline during the winters of 2062 and 2064. Clearly in 2062 (Figure 8, bottom panel) the thermocline is maintained at a relative level of 0m AHD in early May and deepens to approximately -20m AHD by the start of September. This is in stark contrast to the temperature profile through the winter of 2064. Keeping in mind that the thermocline is the depth in the water column of greatest temperature change in a stratified lake (See Glossary of Terms), it can be seen that in early May of 2064 the thermocline deepens from approximately -10m AHD down to approximately -45m AHD by the end of June. In early July there are 2 days when it deepens to approximately -60m AHD. Immediately following this short period of deepening, a new surface thermocline develops between approximately +10m AHD and 0m AHD. This is not discernible in the 'coarser' thermal profile shown in Figure 6 for the complete modelling period. This strong, near surface thermocline is maintained until 3 days in early August 2064 when another cool period breaks this near surface thermocline down with the thermocline deepening to -60m AHD for this 3-day period. Following this relatively short period of partial mixing, a strong surface thermocline re-establishes and is maintained until 1 September 2064, after which time enhanced seasonal warming of the mine pit lake surface mixed layer begins concurrent with the onset of summer.

3.2.3 Upstream inflow Tracer October 2047 to September 2067 for flow through scenario

Figure 10 shows the upstream inflow tracer for the period of the simulation. Inflow begins with the first McArthur River flows >25m AHD that follow the opening of the levees on 17 March 2058. In the modelled period following the levee openings, the concentration of upstream inflow above 50m AHD varies seasonally between approximately 20% and 80% with the highest concentrations evident toward the end of the simulation period. Deeper in the water column there is some deepening of the upstream inflow tracer peaking in the winters of 2064 and 2065 when water between -50m AHD and -90m AHD shows increased inflow tracer concentrations ranging from approximately 25% down to approximately 10% or less at -90m AHD. This is associated with the deeper seasonal mixing during the 2064 winter period described above in Section 3.2.2. It should be noted that, as shown in Section 3.2.2 year to year differences in the meteorological conditions will change the extent of mixing and hence the vertical distribution of surface waters (as tracked by the tracers of the inflows). Once distributed into the metalimnion and hypolimnion, which experience far smaller mixing rates compared to the surface mixed layer, these waters will remain for a longer time period in the lake due to a lack of flushing. Over time their vertical distribution will spread due in part to small simulated mixing events such as shear between stratified layers, steady state diffusion and repeated top-down mixing events during cooler/windier years. As such, the profile of tracers bears no relationship to, and should not be confused with, the depth of the thermocline.

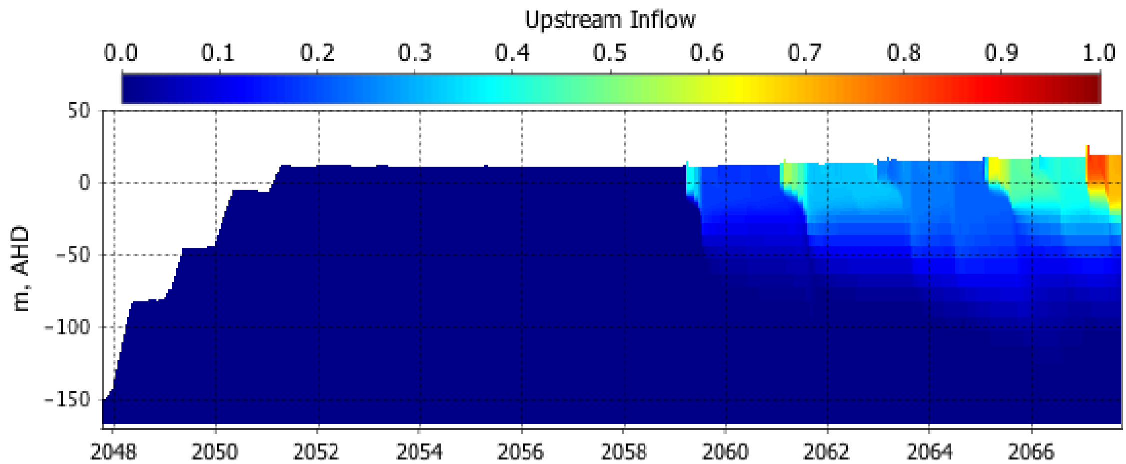


Figure 10: Upstream inflow tracer for a flow through scenario

3.2.4 Downstream inflow Tracer October 2047 to September 2067 for flow through scenario

As noted above, in the flow through scenario configuration, flows in the McArthur River with elevations between 20m AHD and 25m AHD will enter the mine pit lake over the downstream levee (20m AHD) via the channel constructed to the downstream portion of the diversion channel (See Figure 3). They will however, be predominantly much lower than flows that enter from the upstream levee when the river elevation exceeds 25m AHD (See Figure 5). Profiles of the fate of the downstream inflow for a flow through are shown in Figure 11.

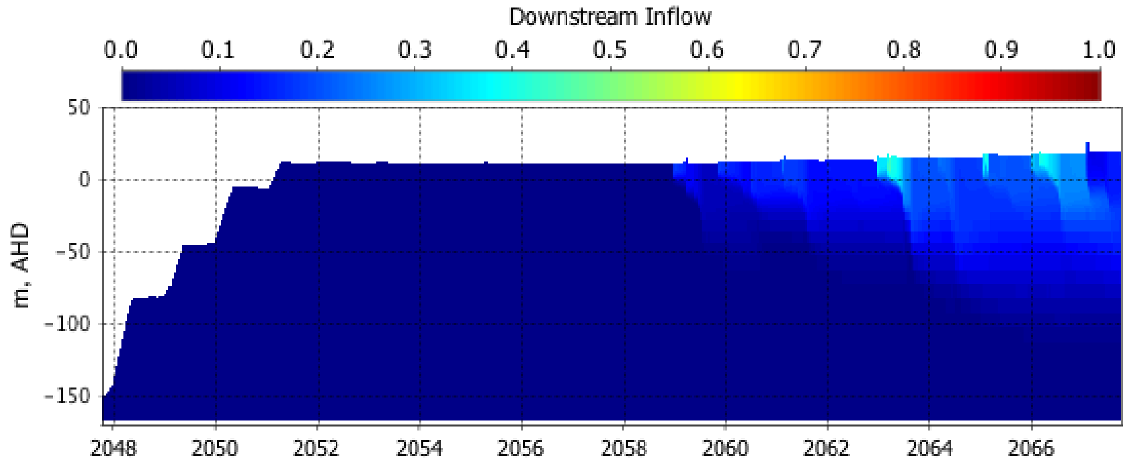


Figure 11: Downstream inflow tracer inflow tracer for a flow through scenario

In comparison to the upstream inflow tracer described in Section 3.2.3, the downstream inflow tracer in Figure 11 approximates its obverse with its destination in the water column being in many ways the opposite of the upstream inflow tracer.

3.2.5 Retention time in the mine pit lake October 2047 to September 2067 for flow through scenario

Figure 12 shows a profile of the water retention time in the profile of the mine pit lake over the modelled period. As expected during the filling and isolation stage up until the opening of the levees on 17 March 2058, the water age steadily increases throughout the water column. Following this, water below -100m AHD ages steadily from approximately 3,500 days to approximately 6,000 days by the end of the 20-year simulation in 2067. Theoretically, this water should be over 7,000 days old. The effect of rainfall and comparatively small inflows for the local catchment, combine to foreshorten this theoretical retention time.

The near-surface water age from +20m AHD down to approximately -20m AHD responds to the series of summer inflows and varies seasonally in response to these. A clear example of this is during the relatively 'dry' period from late 2059 to early 2061 when no upstream inflow entered the mine pit lake (See Figure 5), the retention time stayed fairly stable at approximately 2800 days from mid-2059 until early 2061. At this time, high flows dominated by upstream inflow entered the mine pit lake and decreased the surface retention time ('water age') above approximately 0m AHD to <2000 days.

The partial mixing event in the winter of 2064 described in Section 3.2.2, caused some migration of older, deeper water into the surface regions of the mine pit lake and the decrease of deeper water retention time. The retention time of water between approximately -30m AHD and -70m AHD subsequently increased from late 2064 on, punctuated in mid-2066 by another comparatively moderate mixing event that caused an increase in water age from the surface down to approximately -40m AHD.

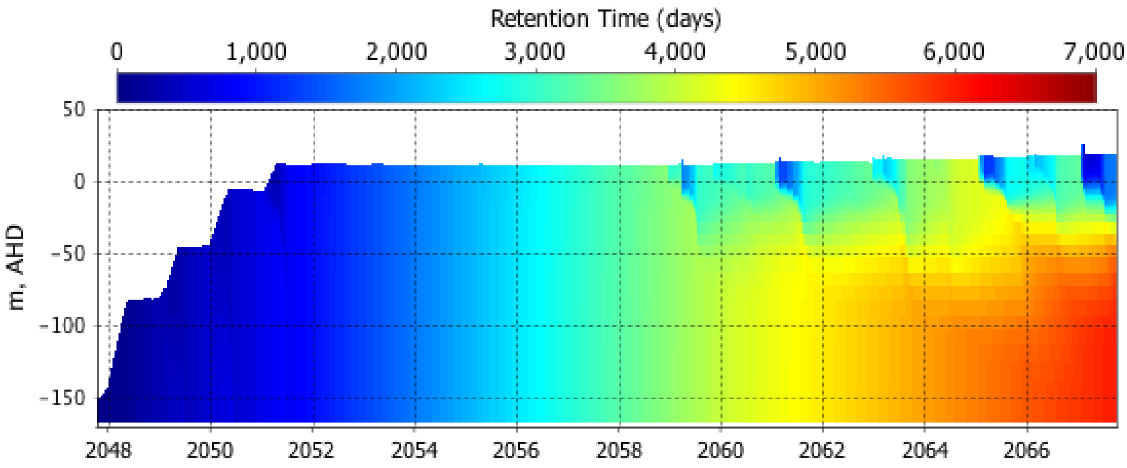


Figure 12: Retention time in the mine pit lake for flow through scenario

3.3 Outputs for backflow scenario

The backflow scenario involves two levees, one on the upstream entry of the McArthur River into the mine pit lake and another on the outlet of the mine pit lake entering the old McArthur River channel. These are at elevations of 44 m AHD and 20 m AHD respectively. This configuration prevents inflow entering the mine pit lake from the upstream McArthur River with only the downstream levee receiving inflows (See Figure 3). On 17 March 2058 the downstream levee is opened to allow flow from the downstream McArthur River to flow in and out of the mine pit lake through the old downstream McArthur River channel concurrent with flows in the river being greater than 20m AHD (See Figure 3). On 23 March 2058, 6 days after the levee is opened, a cyclone as described in Section 2.1.4 above, directly impacts the lake. The WRM modelled flow outputs for this scenario are shown in Figure 13.

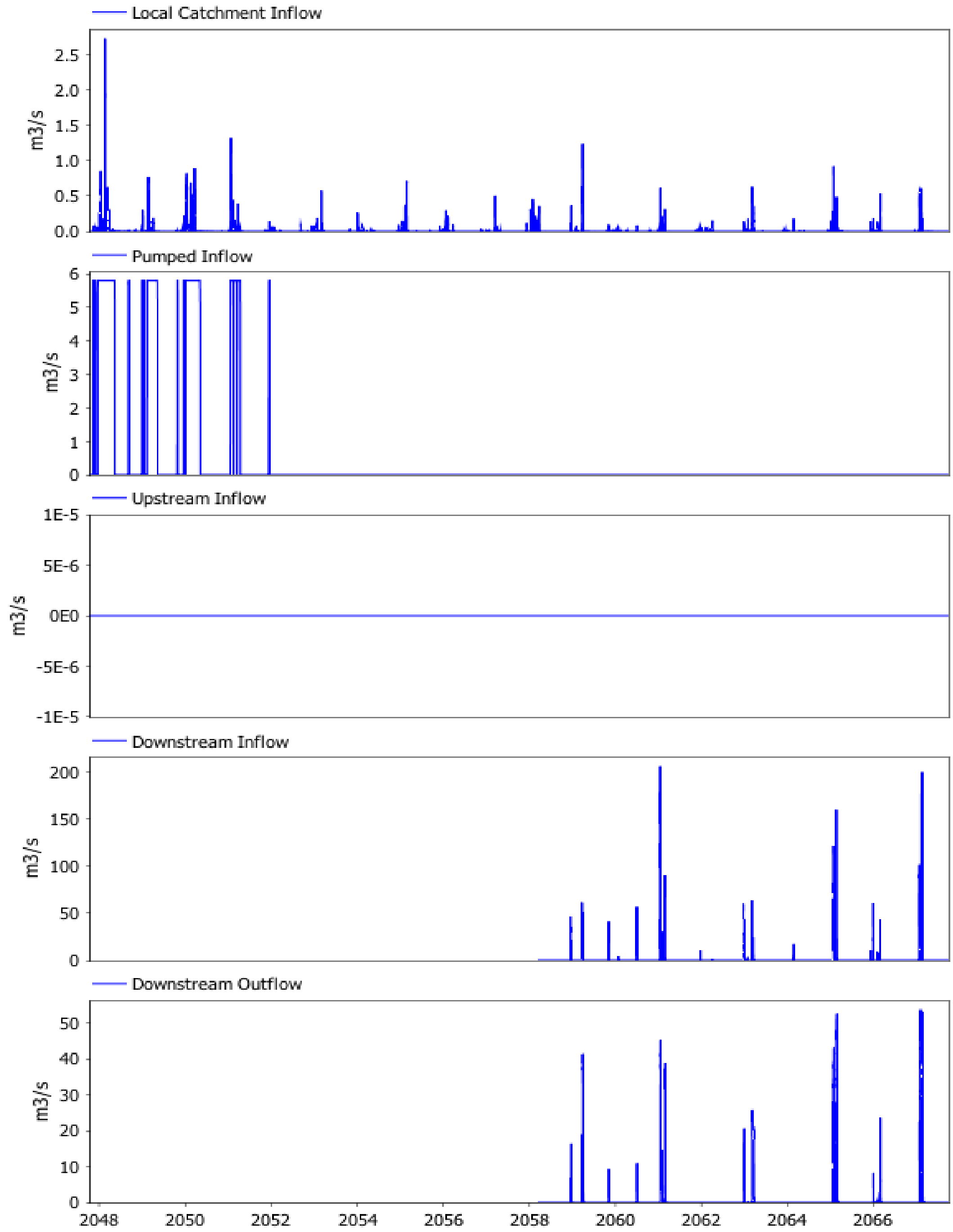


Figure 13: Flows entering and exiting the mine pit lake for a backflow scenario (WRM data).

3.3.1 Temperature profile October 2047 to September 2067 for a backflow scenario

Following the opening of the downstream levee on 17 March 2058, the seasonal thermal profile for the backflow scenario shown below in Figure 14 is similar to that for the flow through scenario shown in Figure 6. This is not surprising since this scenario is in essence a flow-in and flow-out regime with the primary difference that both flows enter and exit through the common downstream levee opening. The deeper partial mixing in the winter of 2064 described for the flow through scenario is evident with similar, although slightly less pronounced, deepening.

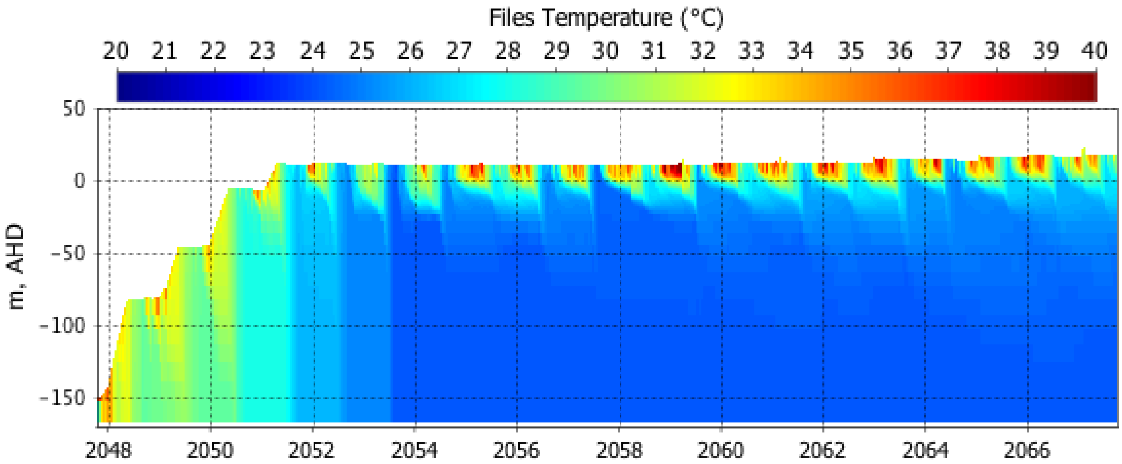


Figure 14: Temperature profile October 2047 to September 2067 for a backflow scenario

A zoom of the winters of 2062 and 2064 is available for the backflow case but is virtually exactly the same as that shown for the flow through scenario described in Section 3.2.2 and shown in Figure 8 and Figure 9 and is not included in the interests of brevity. The trend is the same such that in early May of 2064 the thermocline deepens from approximately -10m AHD down to approximately -45m AHD by the end of June. In early July there are 2 days when it deepens to approximately -60m AHD. Immediately following this short period of deepening, a new surface thermocline develops between approximately +10m AHD and 0m AHD. This is not discernible in the 'coarser' thermal profile shown in Figure 14 for the complete modelling period. This strong, near surface thermocline is maintained until 3 days in early August 2064 when another cool period breaks this near surface thermocline down with the thermocline deepening to -60m AHD for this 3-day period. Following this relatively short period of partial mixing, a strong surface thermocline re-establishes and is maintained until 1 September 2064 after which time enhanced seasonal warming of the mine pit lake surface mixed layer (epilimnion) begins concurrent with the onset of summer.

3.3.2 Downstream inflow Tracer October 2047 to September 2067 for a backflow scenario

All inflows in the backflow scenario enter the mine pit lake via the downstream levee when flows in the McArthur River exceed -20m AHD. Figure 15 shows the fate of these flows in the water column of the mine pit lake following opening of the levee on March 17, 2058.

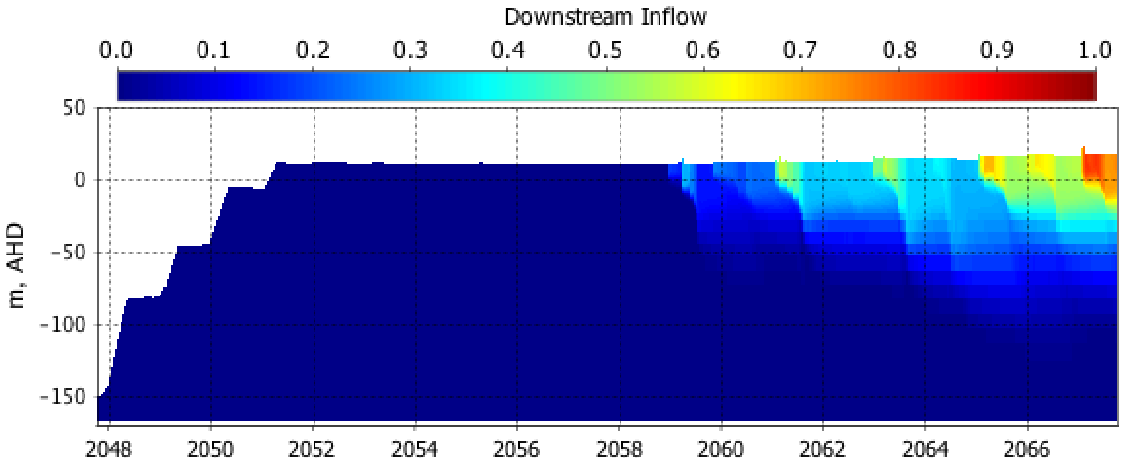


Figure 15: Downstream inflow Tracer for backflow scenario

Again, the downstream inflow tracer for the backflow scenario is quite similar to the upstream inflow scenario shown and discussed in Section 3.2.3 for the flow through scenario. The main differences are that in Figure 15, there is a steadier summer (wet season) increase in the fraction of downstream inflow at depths above -30m AHD even though they vary seasonally with inflows. As with the flow through scenario, the exception is the winter of 2064 when the downstream inflow tracer deepens to approximately -90m AHD.

3.3.3 Retention time in the mine pit lake October 2047 to September 2067 for backflow scenario

Figure 16 shows the retention time in the profile of the mine pit lake for a backflow scenario. The seasonal pattern shows that, following the levee opening in March 2058, retention times in the surface layer down to approximately -10m AHD vary seasonally with shortened retention times of less than approximately 2,000 days during summer inflow periods increasing to 3,000 to 4,000 days in the winter period when there is little or no inflow. Again, the exception is the winter of 2064 when retention times increase to approximately 4,500 days due to several short mixing events in July and August of that year. This mixing introduces older, deeper water between approximately -50m AHD and -90m AHD into the surface of the mine pit lake.

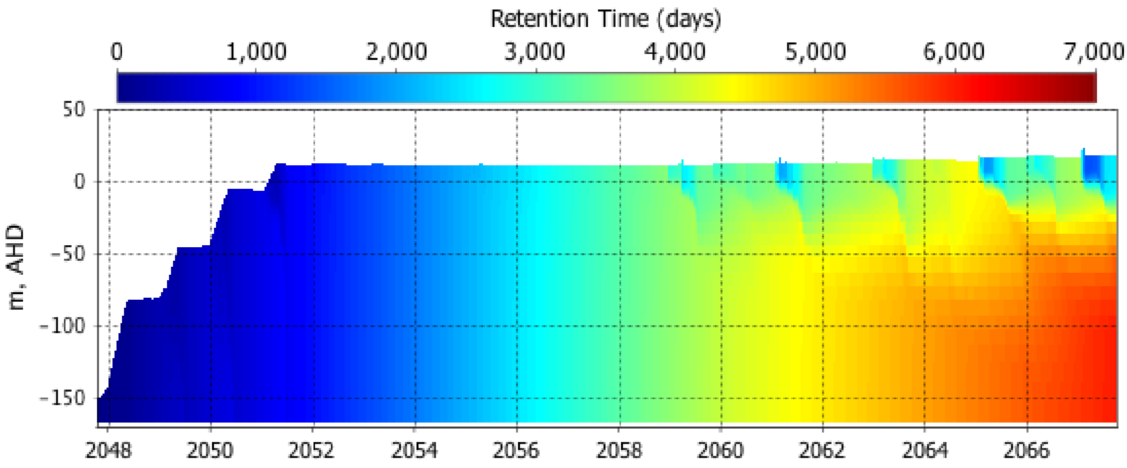


Figure 16: Retention time in the mine pit lake for backflow scenario

3.4 Outputs for the 'extreme event' scenario

The sequence of events for the 'extreme event' scenario (as developed by WRM) follow:

1. The mine pit lake is filled and isolated from 1 October 2047 to 17 March 2058.
2. On 17 March 2058 the Mine Levee Wall downstream opening is constructed at an Invert level of 20m AHD
3. On 18 March 2058 a 0.1% AEP (1,000-year ARI) flood event commences. At the peak of this flood on 23 March 2058 a cyclone impacts directly over the mine pit lake.
4. The Mine Levee Wall fails at the upstream opening location near the peak of the flood event at 0300 hours on 23 March 2058. This causes the base of the Mine Levee Wall downstream opening to also fail. The adopted failure openings are as follows:
   - For the Mine Levee Wall upstream failure opening the invert level falls to 20m AHD
   - For the Mine Levee Wall downstream opening failure opening the invert level falls to -18m AHD
5. At 0000 hours on 6 April 2058 the Mine Levee Wall upstream failure opening is repaired (to 44m AHD). The Mine Levee Wall downstream opening is repaired to its original configuration.

In order to model the 1:1000-year ARI flood, AEM3D required a number of modifications to those shown in Table 2. These were:

- The time step was reduced from 60 to 10 seconds to get through the peak of the 1:1000 ARI flood;
- 30 m of additional model layers (3x10m near bottom) were added to the surface of the mine pit lake to account for the increase in water level during the peak of the flood. These layers that fill during the flood are 1 m thick;

- Weir calculation of outflows were turned off in AEM3D so the model is forced only with the water balance flow predictions of inflow and outflow derived from the spreadsheets provided by WRM;
- The failure of the upstream and downstream levees ('extreme event' scenario) were simulated and included cyclone weather conditions in March 2058;
- The maximum depth of inflow was increased to cover the surface 10m (up from 2m). This was necessary to keep the model stable during the very large inflow event.
- The Salinity of inflows is assumed to be 0 PSU during the flood event. As noted in Section 2.1 ambient EC levels (a correlate of salinity) are quite low in the McArthur River (<500 µS/cm) and would certainly be much lower than this in a flood hydrograph of this magnitude;
- Flow-through and failure ('extreme event') simulations started with the same initial condition as the flow through and backflow scenarios;
- The mine pit lake configuration is unchanged until the end of the assessment period on 30 September 2067.

Flows used for the 'extreme event' scenario modelling are shown below in Figure 17. The following Figure 18 shows a zoom of the flows from 1 March 2058 to 30 April 2058.

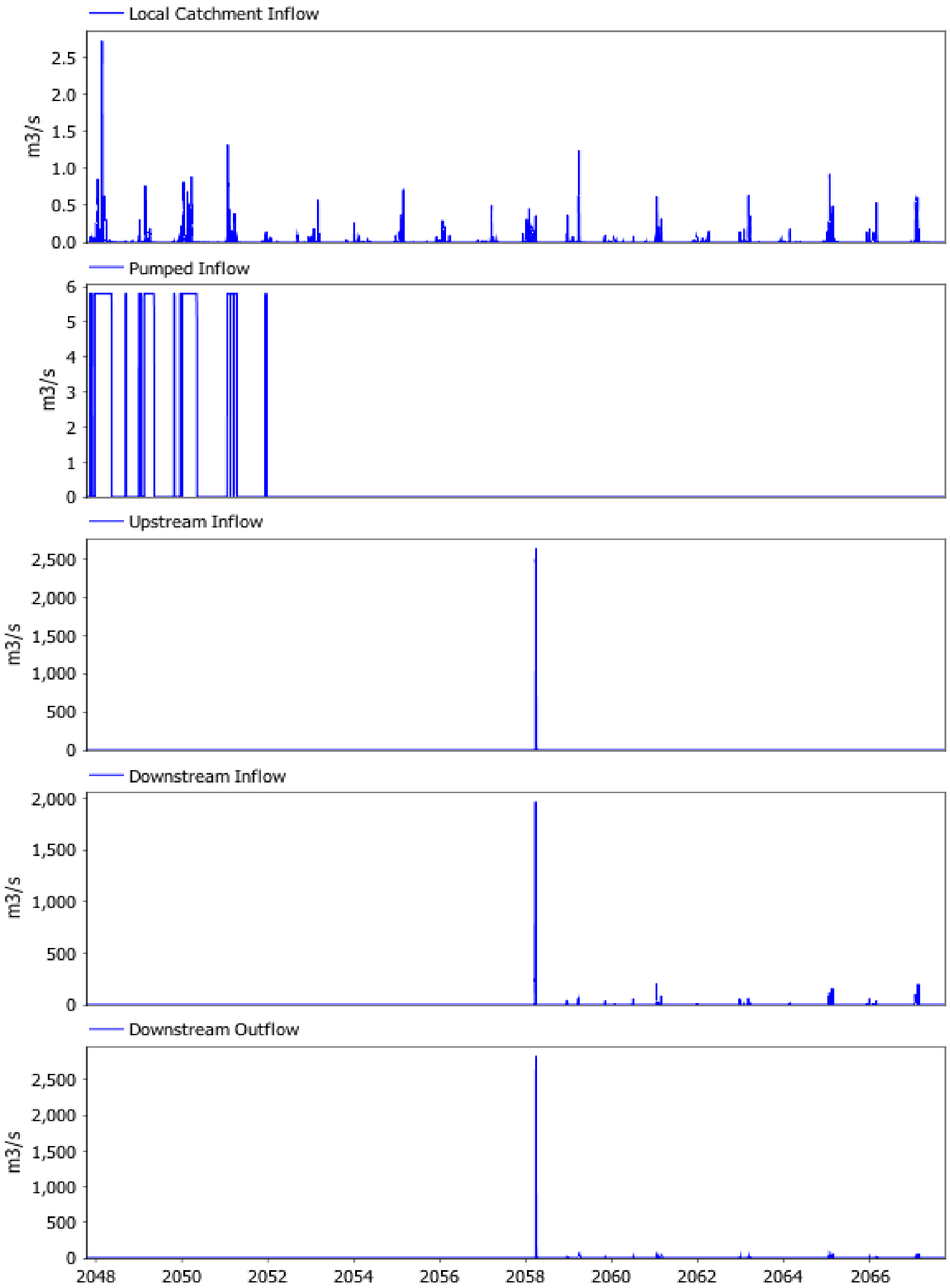


Figure 17: Flows entering and exiting the mine pit lake for an 'extreme event' scenario (WRM data).

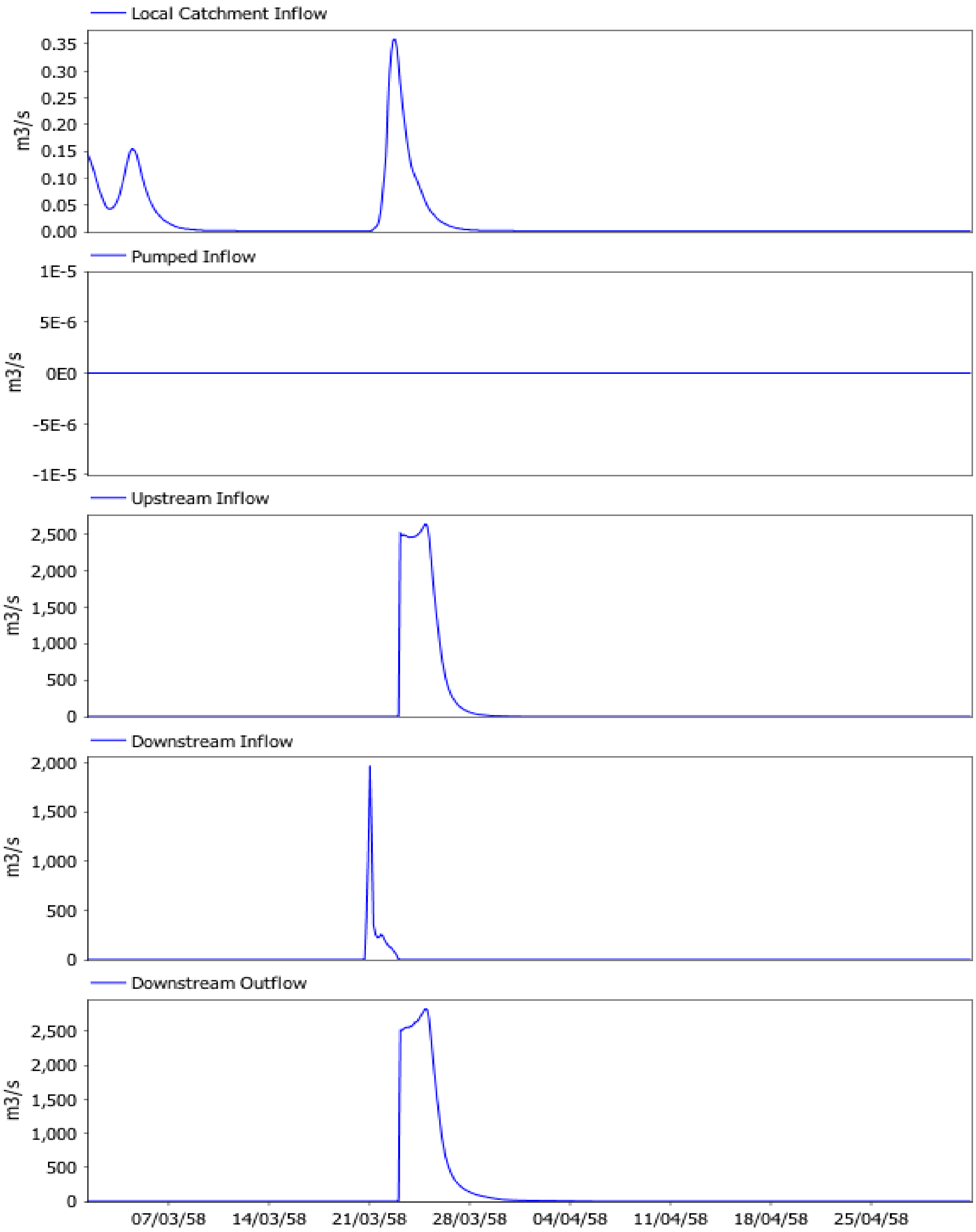


Figure 18: Zoom of flows entering and exiting the mine pit lake for an 'extreme event' scenario, March to April 2058 (WRM data).

Local catchment inflow in panel 1 of Figure 18 shows a strong increase during the flood period but these flows are insignificant compared to those sourced from upstream inflow and downstream inflow shown in panels 3 and 4 respectively.

It should be noted that downstream inflow increases markedly (panel 4 in Figure 5) at the start of the flood but before the coinciding failures of both the upstream and downstream levees. After this, downstream inflow ceases and flood inflow from the failed upstream levee inundates the mine pit lake.

3.4.1 Temperature profile October 2047 to September 2067 for 'extreme event' scenario

Following the failure of both upstream and downstream levees on 23 March 2058, there is a significant deepening of the surface mixed layer (epilimnion) with partial mixing extending to approximately -110m AHD (Figure 19). This is accompanied by a rapid cooling of the near surface of the water column from approximately 35°C to approximately 27°C. Water between approximately -10m AHD to -70m AHD warms from approximately 24°C to 27°C. After the repairs in April 2058 and following the summer of 2059 this warmer water tends to distribute into the deeper regions of the mine pit lake causing an overall warming of the deep hypolimnion. This warming is also assisted by the partial mixing event in the winter of 2064 already described in Sections 0 and 3.3 for the flow through and backflow scenarios.

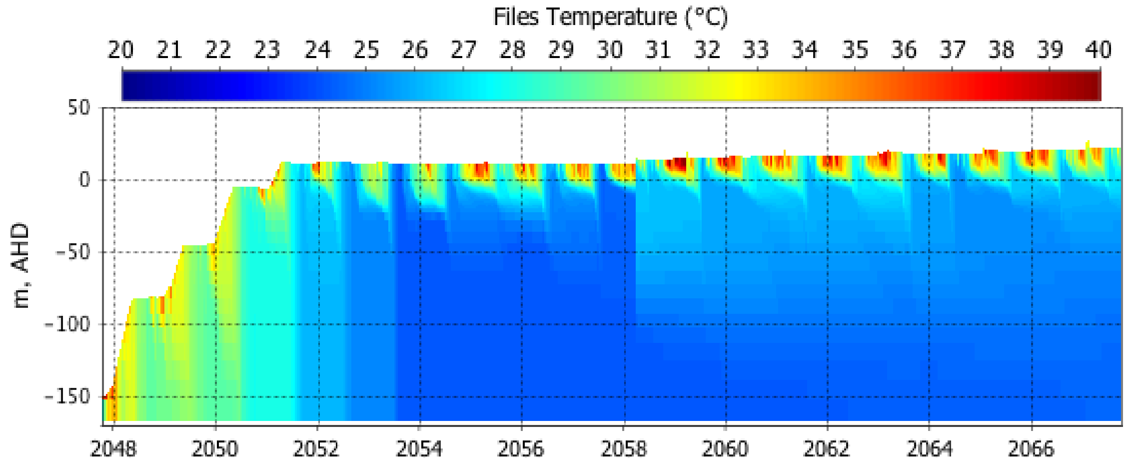


Figure 19: Temperature profile October 2047 to September 2067 for 'extreme event' scenario

Figure 20 is a zoom of the period from 1 March 2058 to 30 April 2058 and shows the more immediate reaction of the mine pit lake's thermal profile to the flood event.

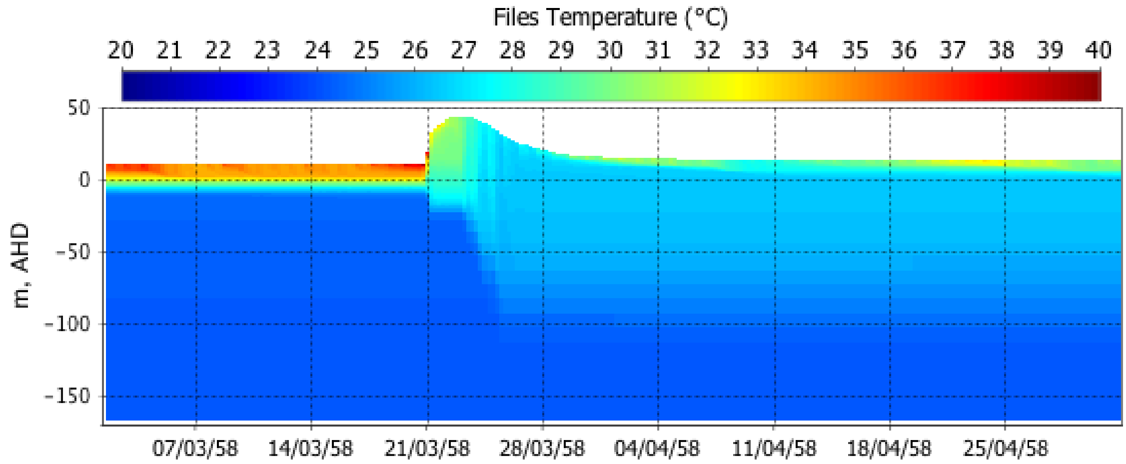


Figure 20: Zoom of temperature profile in the mine pit lake for an 'extreme event' scenario, March to April 2058.

It is noted that some surface warming is evident in Figure 20 toward the last 2 weeks of April. The potential 'recovery time' of the mine pit lake is better shown by the flow tracers and retention time graphs that follow.

3.4.2 Upstream inflow Tracer October 2047 to September 2067 for 'extreme event' scenario

Figure 21 shows the fate of the upstream tracer flow in the mine pit lake following the levee opening and their failures on 23 March 2058. As expected, following the flood event and even after the levee repairs in April 2058 the surface layer down to -50m AHD is dominated by upstream inflow until the 'wet season' summer flows of 2059. During this 2059 summer flow period, the surface down to approximately -10m AHD decreases to approximately 60% upstream inflow. Seasonally from then on, the proportion of upstream inflow down to approximately -50m AHD, decreases steadily with each yearly summer flow period until by the end of the simulation on 30 September 2067 the proportion of upstream inflow down to approximately -20m AHD is <30%. As with the flow through and backflow scenarios, the deepening in the winter of 2064 tends to 'push' some of the upstream inflow water deeper into the water column down to approximately -130m AHD even though the thermocline only reached approximately 60m AHD during this partial mixing event (See Figure 9). It is repeated that the fate of flow tracers is not analogous to stratification but the trend shown in Figure 21 does indicate a gradual recharging of the mine pit lake with water from sources other than upstream inflow.

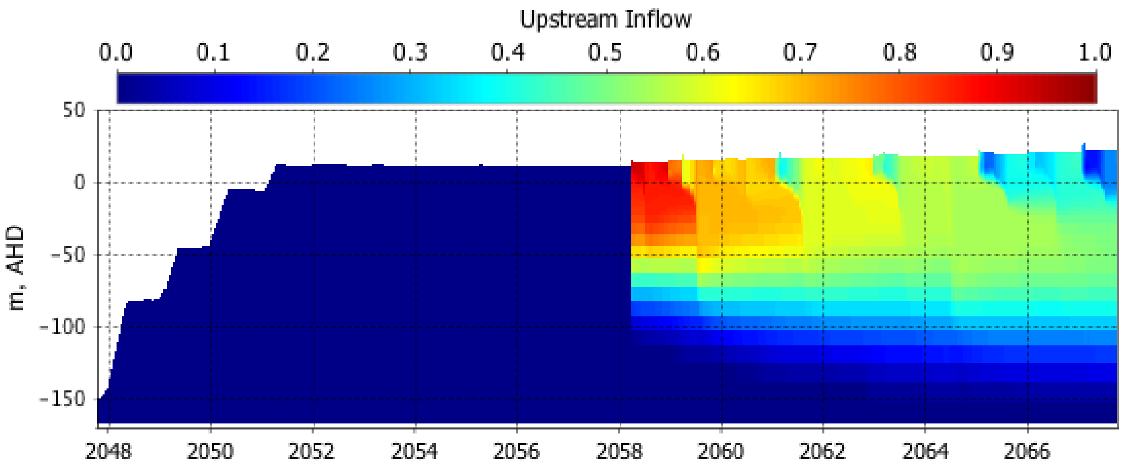


Figure 21: Upstream inflow Tracer October 2047 to September 2067 for 'extreme event' scenario

As noted previously, the only other significant source of 'recharge' following the levee repairs of April 2058, is via the downstream levee.

3.4.3 Downstream inflow Tracer October 2047 to September 2067 for 'extreme event' scenario

Figure 22 shows the fate of the downstream inflow tracer following the major flood on March 23, 2058. As was the case with the equivalent diagrams described in Section 3.3 for the backflow scenario, Figure 22 is the obverse of the upstream inflow tracer shown in Figure 21. The proportion of downstream inflow in the surface layer down to approximately -10m AHD steadily increases until toward the end of the simulation in 2067, in which year the proportion ranges from 90% at the start down to approximately 70% at the end of September that year.

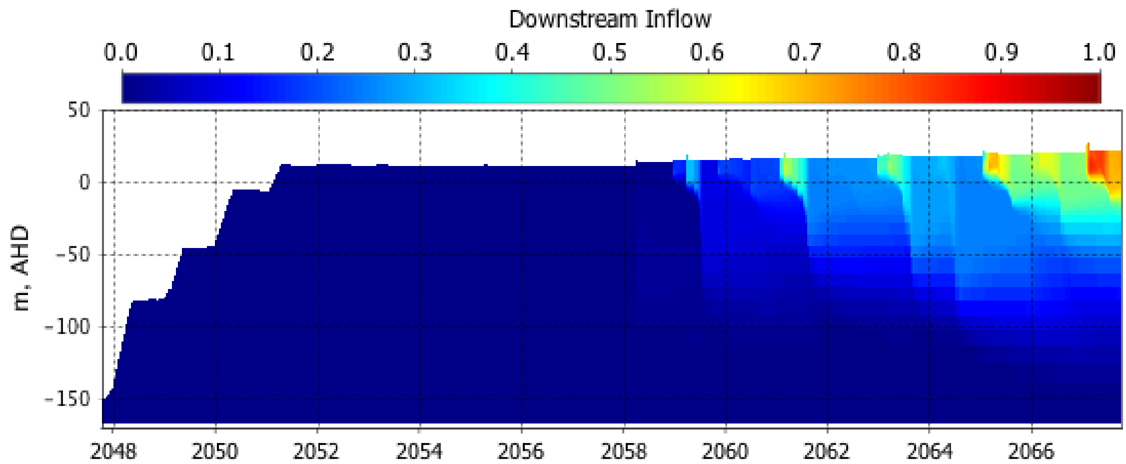


Figure 22: Downstream inflow Tracer October 2047 to September 2067 for 'extreme event' scenario

3.4.4 Retention time in the mine pit lake for the 'extreme event' scenario

Figure 23 shows the retention time in the mine pit lake for the 'extreme event' scenario. Immediately following the levee failures in March 2058 the retention time in the surface layer, down to approximately -90m AHD, falls rapidly ranging from <500 days near the surface to approximately 2500 days at -90m AHD. Water in this region of the profile seasonally trends toward longer retention times following the 2059 summer flow period, although briefly interrupted by the previously described two short mixing events in July and August 2064. Below -100m AHD, the water age continues to increase from approximately 3,500 days at the time of the levee failures to approximately 5,000 days at the end of the simulation period in September 2067. This trend is subject to a minor perturbation at -90 to -100m AHD in the winter of 2064 when two short deepening events cause a small, transient decrease in water age in this depth range. This deepening has been discussed in detail in the flow through and backflow scenarios in Sections 0 and 3.3 respectively.

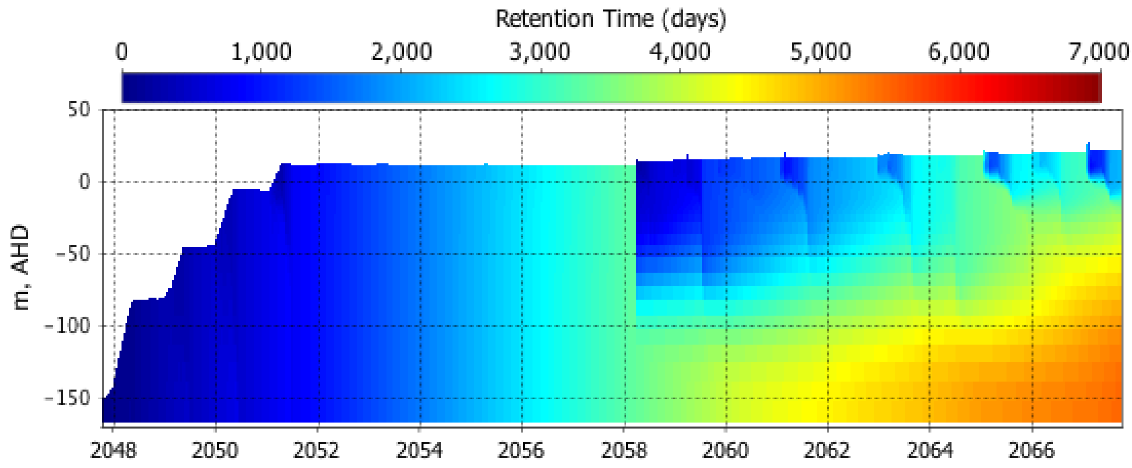


Figure 23: Retention time in the mine pit lake for the 'extreme event' scenario

4. Summary Discussion

4.1 Flow through scenario

The temperature profile seasonal structure for the flow through scenario shows that a significant thermocline structure is maintained at approximately -0m to -10m AHD during summer months with seasonal winter deepening due to partial mixing extending to around -50m AHD. This winter deepening is due mainly to seasonal decreases in air temperature and insolation rates but is generally confined to the upper portion of the water column above approximately -50m AHD.

Seasonal winter deepening varies between years and toward the end of the simulation period (2060 onward) some partial mixing occurs below -50m AHD. In particular the winter of 2064 shows weak partial mixing to approximately -70m to -80m AHD. This is associated with cooler than average winter air temperatures in this year along with a longer than usual cool winter period. This has only a minor influence on waters above -50m AHD.

This is shown by a zoom enlargement of the thermal profile for the winter of 2064. In early May of 2064 the thermocline deepens from approximately -10m AHD down to approximately -45m AHD by the end of June. In early July there are 2 days when it deepens to approximately -60m AHD. Immediately following this short period of deepening, a new surface thermocline develops between approximately +10m AHD and 0m AHD. This is not discernible in the ‘coarser’ thermal profile shown for the complete modelling period. This strong, near surface thermocline is maintained until 3 days in early August 2064 when another cool period breaks this near surface thermocline down with the thermocline deepening to 60m AHD for this 3-day period. Following these short periods of partial mixing, a strong surface thermocline re-establishes and is maintained until 1 September 2064 after which time enhanced seasonal warming of the mine pit lake surface mixed layer begins concurrent with the onset of summer.

Transport of water from the hypolimnion to the epilimnion of the mine pit lake in the winter of 2064 would have been dominated by transport from regions above -50m AHD with two short periods of two days in July and three days in August when some water may have been transported from layers up to -60m AHD deep. Considering the shape of the mine pit lake and the short period of deeper partial mixing, the proportional volume of water from below -50m AHD transported into the much larger volume epilimnion, would have been very small.

4.2 Backflow scenario

Following the opening of the downstream levee on 17 March 2058, the seasonal thermal profile for the backflow scenario shown below in Figure 14 is similar to that for the flow through scenario. This is expected since this scenario is in essence a flow-in and flow-out regime with the primary difference that both flows enter and exit through the common downstream levee opening. The deeper partial mixing in the winter of 2064 described for the flow through scenario is evident with similar, although slightly less pronounced, deepening.

4.3 Extreme event scenario

In the modelled hypothetical 'extreme event' scenario, following the failure of both upstream and downstream levees on 23 March 2058, there is a significant deepening of the surface mixed layer (epilimnion) with mixing extending to approximately -110m AHD. This is accompanied by a rapid cooling of the near surface of the water column from approximately 35°C to approximately 27°C. Water between approximately -10m AHD to -70m AHD warms from approximately 24°C to 27°C. After the repairs in April 2058 and following the summer of 2059 this warmer water tends to distribute into the deeper regions of the mine pit lake causing an overall warming of the deep hypolimnion. This warming is also assisted by the partial mixing event in the winter of 2064 already described in the flow through and backflow scenarios.

Immediately following the levee failures, the retention time in the surface layer down to approximately -90m AHD, falls rapidly ranging from <500 days near the surface to approximately 2,500 days at -90m AHD. Water in this region of the profile seasonally trends toward longer retention times following the 2059 summer flow period, although briefly interrupted by the previously described two short mixing events in July and August 2064. Below -100m AHD, the water age continues to increase from approximately 3,500 days at the time of the levee failures to approximately 5,000 days at the end of the simulation period in September 2067. This trend is subject to a minor perturbation at -90 to -100m AHD in the winter of 2064 when two short deepening events cause a small, transient decrease in water age in this depth range. This deepening has been discussed in detail in the flow through and backflow scenarios in Sections 0 and 3.3 respectively. This trend of steadily increasing age in waters below approximately -100m AHD to the bed of the mine pit lake indicates the absence of any turbulence originating from the surface of the water body even during the simulated 'extreme event' scenario.

Figures 19 shows that, even in the 'extreme event' scenario, there is no mixing energy impinging on the bed of the pit lake where sediment material/tailings will exist. The relative mass (or Specific Gravity) of this sediment/tailings material is 3.2 (GHD, 2017) and is located well below -150m AHD. Thus, the absence of significant mixing energy reaching the bed of the mine pit lake renders the resuspension of this material by vertical turbulence transport (associated with seasonal mixing), virtually impossible.

5. References

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APPENDIX 1: CONTAMINANTS OF CONCERN RELEASE TRACER

Figure 24 shows the bathymetry of the mine pit lake and the location of a two-dimensional profile 'curtain' represented by red dots.

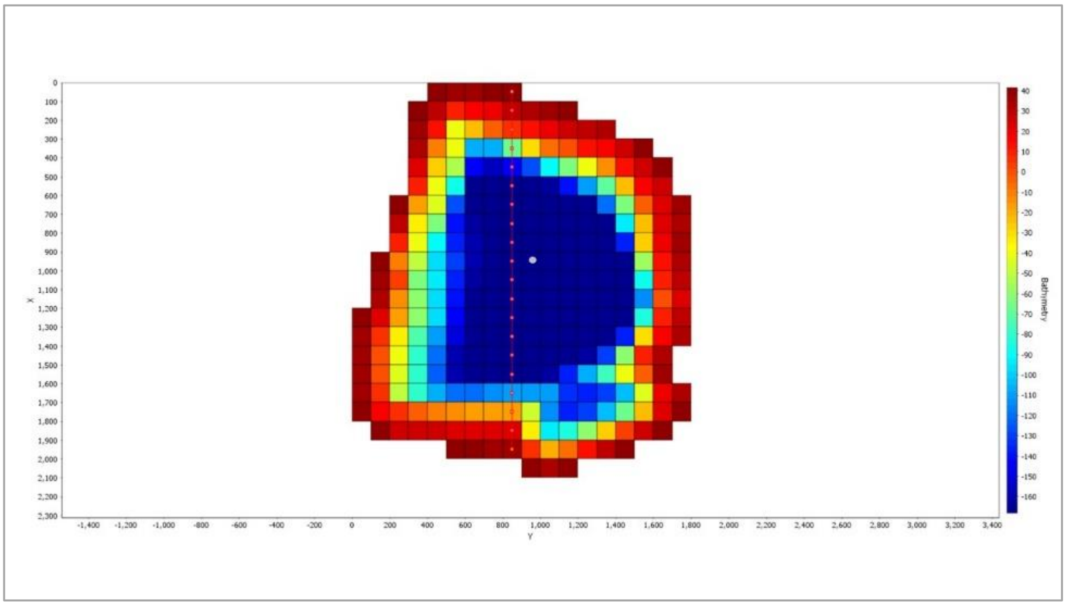

Figure 24: Bathymetry showing output locations exported as AEM3D results for the flow through scenario. The red line shows the location of the 2D Curtain (the grey dot indicates the location of the 1D profile extraction information discussed in the main body of this report). The bathymetry legend is m (AHD).

A collage of transverse images of this curtain are shown in Figure 25 and display the accumulation of contaminants of concern (CoC) based on a release rate of any conservative, scalar CoC at an arbitrary rate of 0.5mg/m^2/day for all mine pit lake wall and bed surfaces below -30m AHD. The collage in Figure 25 is a based on the flow through scenario in the MRM mine pit lake (See Section 3.2) over the modelled period 2047 to 2067.

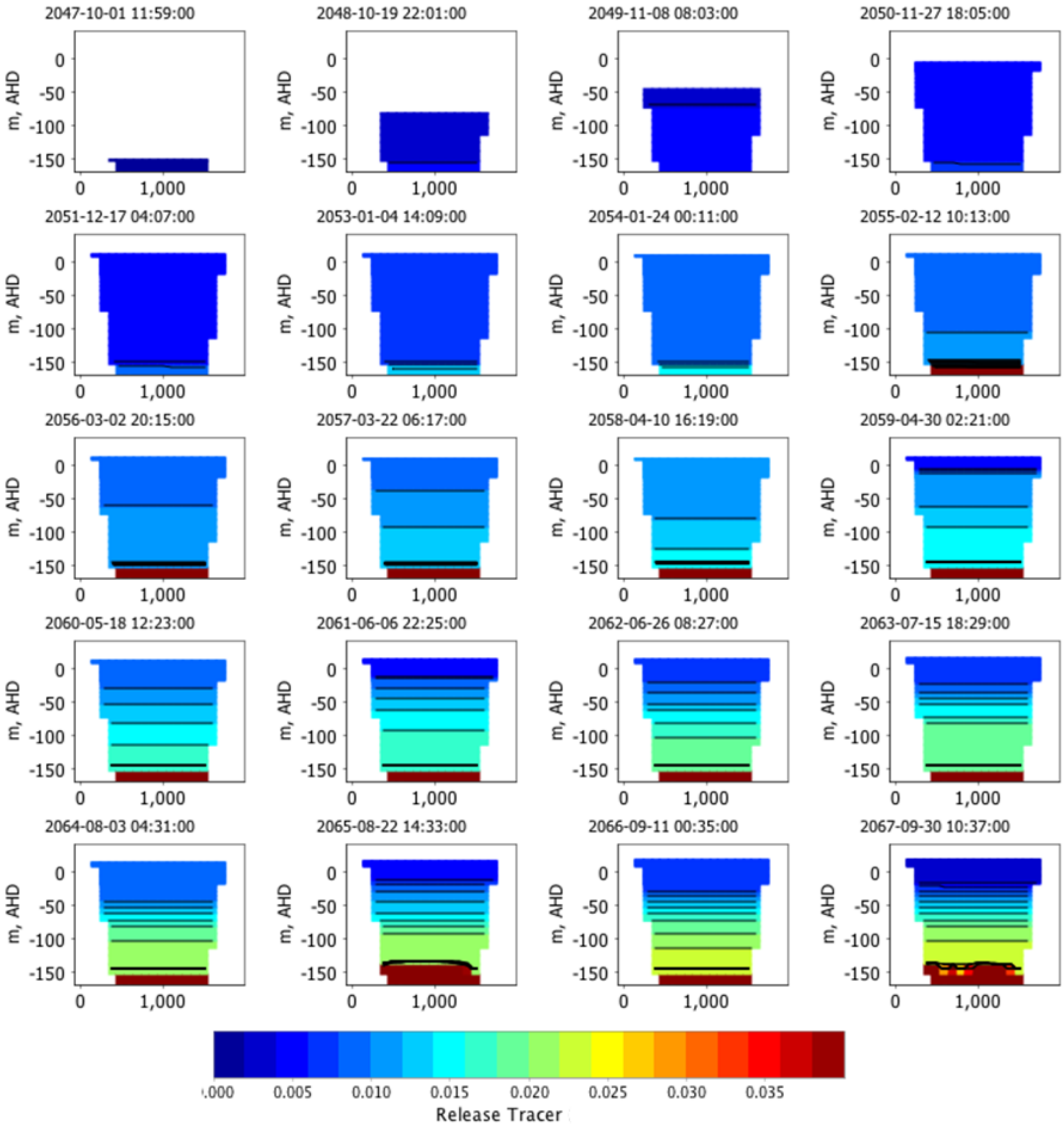

Figure 25: Accumulation of any CoC in the MRM mine pit lake profile over the modelled period 2047 to 2067 based on a release rate of 0.5mg/m^2/day from the walls and bed of the mine pit lake below -30m AHD.

The release tracer units in Figure 25 are arbitrary with the curtain images showing the two-dimensional evolution of the CoC chemocline in the MRM mine pit lake. Clearly the great majority of release material remains toward the bed of the pit lake during the simulation period. It should also be noted that that the CoC release tracer rate is set to an arbitrary 0.5mg/m^2/day and remains constant over the simulation period. Thus, no account is taken of reaction changes based on the shifting chemical equilibrium between the walls and bed (below -30m AHD) and the mine pit lake water that would likely develop over the 20-year simulation period.