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Variable-Density Transport Modeling in Hypersaline Pit Lakes

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ABSTRACT

In Western Australia there is the potential for many pit lakes to become point sources of hypersaline water. The low annual rainfall and high evaporation produces a rainfall deficit, contributing to the development of hypersaline pit lakes. The salinization of pit lakes can affect local and regional groundwater resources, as well as the broader natural environment. The extent of impact on the surrounding groundwater system is largely dependent on the local hydrogeology, which dictates whether the pit lake will act as either a terminal sink or a flow through system. A long-term concern is the downgradient movement of saline plumes from pit lakes, especially in flow-through systems.

In this study we perform variable-density transport modeling using SEAWAT to examine the potential for salinity migration from terminal sink pit lakes in Western Australia. As the pit lake water becomes denser over time due to evapoconcentration, the potential for migration into the groundwater system beneath the pit floor is more probable. SEAWAT model results are compared to constant-density transport results. The comparison indicates that failing to consider density changes in the pit lake water causes underestimation of the plume migration distance. Sensitivity analyses were also conducted to examine the sensitivity of model parameters, such as dispersivity, effective porosity, simulation time, and hydraulic conductivity. Results from this study show that given the low permeability of the bedrock beneath the pit floor, salinity migration from this pit will be limited and will not impact downgradient groundwater dependent ecosystems.

Keywords: salinity, pit lake, transport, density, groundwater

INTRODUCTION

The Cameco Corporation Australia in conjunction with Mitsubishi Development Pty. Ltd. is planning the Kintyre Uranium open-pit development in the East Pilbara region of Western Australia, approximately 80 km south of Telfer on the edge of the Great Sandy Desert. If the project was to eventually move forward utilizing the current mine plan, it could potentially run for approximately 14 years based on a total indicated resource of 55.2 million pounds of U_3O_8. The project is located immediately north of the Karlamilyi (Rudall River) National Park (Figure 1).

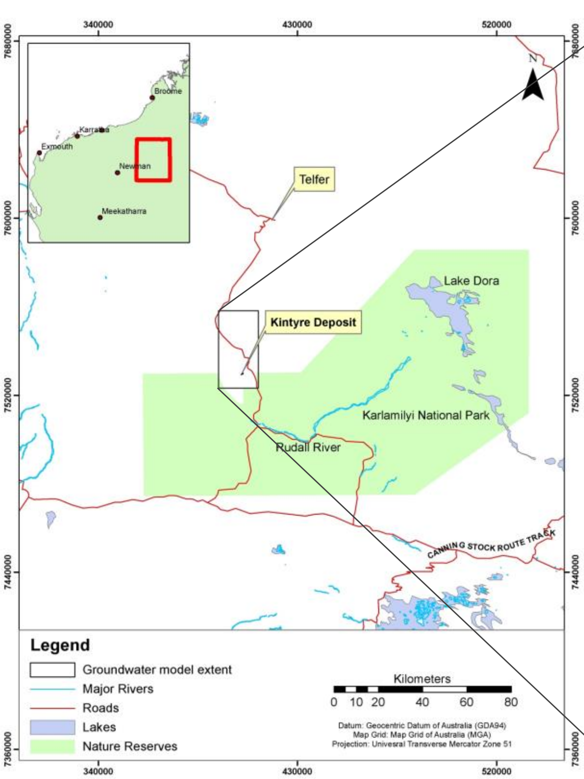

Figure 1 Kintyre Location Map

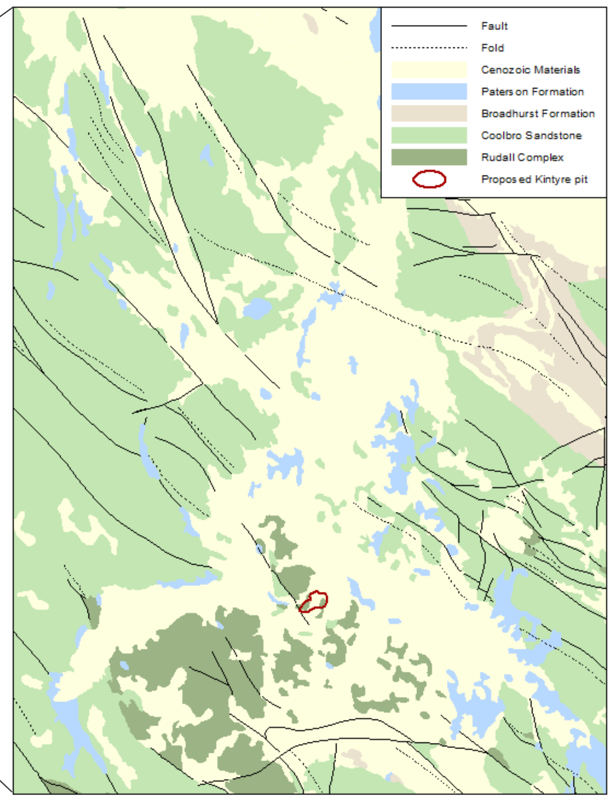

Figure 2 Regional Surficial Geology

The pit is required to be dewatered and, following closure, a pit lake is likely to form. As part of the Environmental Review and Management Program, groundwater, geochemical pit lake and salinity plume models were required to determine the potential for risk to downgradient receptors.

Geological environment

The site is located on a slight topographic high between two branches of the Yandagooge Creek. The creek flows toward the north-northeast between two nearby mountain ranges comprised of sedimentary Neoproterozoic rocks (Broadhurst Formation and Coolbro Sandstone) and metamorphic Paleoproterozoic rocks (Rudall Complex). Yandagooge Creek roughly follows the footprint of a Permian glacial valley that is incised into the Proterozoic rock. The glacial valley is mostly filled with Permian age glaciofluvial and glaciolacustrine sediments (Paterson Formation). The basal Permian is generally tillite and is overlain by sandstone, siltstone, and claystone. Coarser-grained Cenozoic sediments overlie the Permian materials in most locations but tend to be unsaturated. Figure 2 illustrates the site layout and surficial geology.

Pit lakes

The pit shell used in the pit lake model was determined from the mining plan to be predominantly schist with areas of ore host rock, tillite and carbonate material (Figure 3).

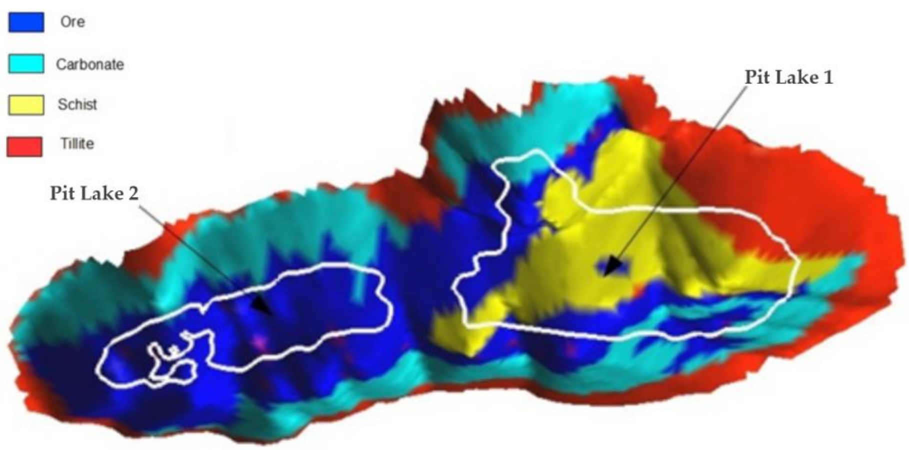

Figure 3 Cross section of pit showing locations of lakes and simplified geology

In semi-arid climates the dissolved constituents in water bodies become highly concentrated and there is an increasing concern that pit lakes will become point-sources of hypersaline groundwater. The Kintyre site occurs in the region with the highest average pan evaporation in Australia, at greater than 4 m per annum. This high evaporation coupled with a low mean rainfall of 372 mm per annum measured at Telfer (BOM, 2014) results in the pit lake becoming an evaporative, 'terminal' sink system (Figure 4) whereby the volume of water egress greatly exceeds ingress and the hydrogeological gradient is towards the pit. McCullough, *et al.* (2013) discusses the feasibility of allowing terminal sinks to form in order to reduce the impact to groundwater systems. The terminal sink draws all groundwater or leachate from tailings or waste rock material towards it, ensuring that it will not leave the footprint of the mine area and downgradient receptors will not be impacted by elevated uranium or other metals.

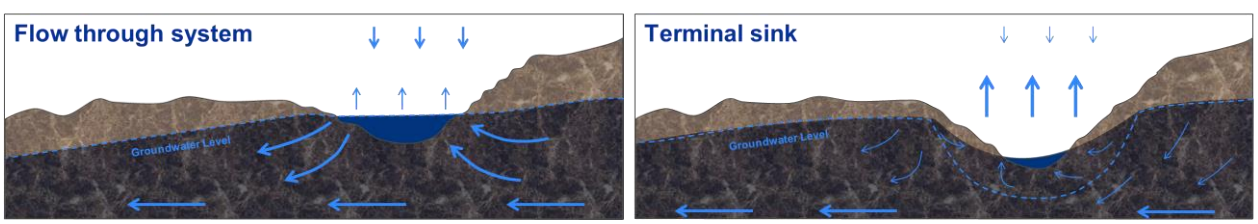

Figure 4 Illustration of pit lake systems

Despite the capture of any elevated element concentrations present in the groundwater by the pit lake evaporative sink, there was concern that a salinity plume could spread, against the flow gradient by diffusion and salinize the surrounding groundwater resources. In order to determine this risk the distance of likely diffusion was modelled.

The geochemical model integrated the pit lake volumes and dimensions to determine the limnological characteristics of the pit lakes. The dimensions of the pit lakes are shown in Figure 3 with the simplified geology used for the pit walls. If the depth of a lake relative to the area is greater than 20 percent, the lake is likely to be permanently stratified (Castendyk and Jewell, 2002). Table 1 shows the maximum depth, surface area, volume and the calculated relative depth. As the relative depth of Lake 1 is 38.6%, which is very much higher than the 20% point above which stratification is likely. It is estimated that Lake 1 will permanently stratify and not be subject to mixing while Lake 2 may not permanently stratify and will be subject to some mixing. Mixing will reintroduce oxygen into the deeper portions of the lake allowing chemical reactions to continue under oxygenated conditions.

Table 1 Pit lakes physical dimensions

Lake	Maximum lake depth (m)	Area (m²)	Maximum volume (m³)	Relative Depth %
Lake 1	139	1.02E+05	5.70E+06	38.6
Lake 2	58	8.69E+04	1.90E+06	17.4

The geochemical model was advanced to 1,000 years although chemical equilibrium was predicted to be reached within 10 years after closure. The final major ion, pH and total dissolved solids concentrations are given in Table 2.

Table 2 Pit lakes major ion concentrations predicted at 1,000 years

mg/L where applicable	Lake 1	Lake 2	mg/L where applicable	Lake 1	Lake 2
pH	7.58	7.52	Magnesium	4.66E+03	5.38E+03
Alkalinity as $CaCO_3$	219	243	Potassium	4.58E+03	5.26E+03
Calcium	432	439	Sodium	3.89E+04	4.49E+04
Chlorine	5.33E+04	6.15E+04	Sulfate	2.46E+04	2.82E+04
Fluorine	29.3	37.2	Total dissolved solids	1.27E+05	1.46E+05

METHODOLOGY

Groundwater flow models were developed and calibrated using MODFLOW-SURFACT to support permitting of the Kintyre project. Both regional and local-scale modelling were performed to assess the potential effects of mining on groundwater dependent flora and fauna (including subterranean) and to evaluate water supply availability. The local-scale model had identical properties to the regional model, but with finer discretization and smaller extents. The flow modelling predicted formation of terminal sink pit lakes. Geochemical models of the pit lakes' water quality using PHREEQC were developed next. The groundwater and geochemical models were used to develop a variable-density transport model using SEAWAT to examine the potential for salinity migration from the predicted terminal sink pit lakes.

Groundwater Flow Model

For modelling purposes, the geologic units were grouped into layers. The layer thicknesses were engineered such that the base of key layers corresponded to the base of the Cenozoic and Permian units where these were present. Outside the vicinity of the paleochannel, the layers were flattened into a subdued representation of topography to maintain layer thickness. Hydraulic conductivity zones were used to represent the different geologic units. The ground surface was used to represent the top of the model.

The uppermost layer (Layer 1) of the model extends from ground surface to approximately 25 meters below ground. Layer 1 includes all Cenozoic materials; where the Cenozoic materials pinch out at the edges of the drainages, Layer 1 includes a portion of the uppermost bedrock unit (Permian or Proterozoic) to maintain layer thickness. Layer 2 includes the first 50 meters of the Permian units, which corresponds to the sandstone, siltstone, and claystone lithologies. Because the Permian units pinch out at the edge of the paleochannel, Layer 2 also includes a portion of the Proterozoic basement rock outside the channel to maintain layer thickness. Layers 3, 4, and 5 each include a 50-meter-thick section of the Permian tillite, with the lateral extent varying based on the paleochannel thickness at that depth. The remainder of each these layers is composed of Proterozoic basement rock to maintain layer thickness. The remaining layers represent the Proterozoic basement rock.

Model recharge was distributed by surficial geology, based on chloride balance data indicating approximate recharge rates. Model hydraulic conductivities and storage coefficients were distributed based on geologic unit.

Geochemical Model

A geochemical model of the final pit lake chemistry was developed using PHREEQC (Cameco Australia, 2013). The major conclusions were:

- The quality of the pit lake water is predicted to be hypersaline;
- Alkalinity is predicted to be moderate over the pit lake life;
- The pH ranges between approximately 7.5 and 8 and is not predicted to become acidic;
- Evaporative losses increase the concentrations of elements such as boron, fluorine, manganese, molybdenum, nickel and uranium over time;
- Salt inputs from the pit walls dissolved by direct rainfall increase the concentrations of arsenic, chromium, copper, lead, nickel, and selenium over time; and
- As a result of the alkaline pH, no iron is predicted to be in solution and aluminium concentrations are predicted to be low.

Variable-Density Flow Model

To simulate transport of salinity or any other solute, the initial concentration must be determined. For this study, the final equilibrium total dissolved solids (TDS) concentration calculated from the geochemical model PHREEQC was used as the initial salinity concentration for each pit lake (Lake 1 and Lake 2). Geochemical model results from PHREEQC do not explicitly calculate TDS concentrations, so the following equation (Csuros, 1997) was used to determine pit lake TDS values:

$$TDS = (0.6 \times Alk) + Na + K + Ca + Mg + Cl + SO_4 + SiO_2 + NO_3 + F \quad (1)$$

The components of this equation are the cations and anions that compose the TDS value. The calculated TDS of Lake 1 used in this model is 127,100 mg/L or 127.1 kg/m³ while the Lake 2 TDS is 146,400 mg/L or 146.4 kg/m³. Both lakes are considered to be hypersaline.

No manual activity corrections were made, beyond those adjustments that occur through the geochemical modelling associated processes. However, oversaturation of species was prevented by allowing chemical precipitation to remove chemical mass from the pit lake, and establish a limit on the maximum dissolved concentration for the associated components of that mineral. As a consequence, over the modelled evolution of both lakes, specific mineral species were predicted to precipitate, including phases containing chloride, sulfate, and fluorine as well as carbonate bearing species and silica.

Two other model parameters required to simulate solute transport are effective porosity and dispersivity. Effective porosity is defined as the ratio of volume of interconnected pore space to total volume of a rock sample. The bedrock units at Kintyre were assumed to have an effective porosity of 0.05 based on literature values for fractured crystalline rock that range between 0 to 0.10 (Freeze and Cherry, 1979).

Estimating dispersivity is challenging when there is no pre-existing solute plume. However, guidance exists regarding dispersivity in relationship to the model grid cell dimensions. The grid Peclet number is the grid spacing (25 m) divided by longitudinal dispersivity, and Peclet numbers should be five or less to minimize numerical errors or numerical dispersion during modelling (Delleur, 2006). For this study, therefore, longitudinal dispersivity is assumed to be 6.25 m, resulting in a Peclet number of 4.

SEAWAT includes a variable-density flow package that requires input values for minimum density, maximum density, as well as the slope of the linear equation of state, which relates fluid density to solute concentration. Density values were determined from standard values of sodium chloride solutions at different concentrations at 25°C (UCSD, 2014). The minimum density is estimated to be 1,075 kg/m³, which is slightly lower than the TDS concentration of Lake 1. The maximum density is estimated to be 1,100 kg/m³ which is slightly higher than the TDS concentration of Lake 2 to compensate for the simulated pit lake water temperature of 32°C. For reference, seawater has a density of 1,025 kg/m³. The slope of the linear equation of state is calculated to be 0.171.

Boundary conditions for the variable-density flow and transport model are identical to previous groundwater models (i.e., General-Head Boundaries around the model grid) except the pit lake cells are specified as either "no flow" for cells located above the water table or as constant head and constant concentration cells. The constant head pit lake cells are set to a hydraulic head equivalent to the final pit lake elevations from the previous groundwater flow model after 1,000 years. Lake 1 is set at 266.8 meters Australian Height Datum (mAHD) and Lake 2 is set at 268.82 mAHD. The constant concentrations at the pit cells are the final equilibrium TDS concentrations from the geochemical model.

Assumptions

Steady-state variable-density modelling was chosen for this study as previous groundwater and geochemical models predicted conditions to 1,000 years and showed that new steady-state conditions were achieved in approximately 100 years. Steady-state modelling was also chosen to reduce computational duration given the small time steps required to perform transport simulations. Assumptions for the variable-density modelling simulations are as follows:

- Precipitation of solids from pit lakes onto the pit lake floor (a process which would reduce permeability of the pit lake floor) is not simulated;

- TDS concentration and water-level elevation is constant in the pit lakes; and
- Salinity concentration of groundwater is zero.

Background salinity concentration of the groundwater was assumed to be zero instead of the mean concentration of 3,300 mg/L to assess only the effects of the pit lake on the groundwater system. This is a conservative assumption, as using zero for the surrounding salinity increases the concentration gradient from the pit lake water to the surrounding groundwater. Using the actual groundwater salinity concentration of 3,300 mg/L would potentially decrease the diffusion of pit-related salinity. Further, since the pit lake water-level elevations and salinity concentrations are held at their maximum simulated values and precipitation of solids from the pit lake are not included; this model is considered to be conservative.

RESULTS AND DISCUSSION

The groundwater flow model was calibrated to within 10% of observed data for both steady state and transient data sets. The calibration data set represented water levels measured in 2011 and 2012 when no onsite pump testing was occurring and as a consequence, the system was assumed to be at steady state. Multiple groundwater pumping tests were performed in a phased and overlapping sequence in six wells during 2011 and in three more wells during 2012. Monitoring data from nearly 50 wells monitored during the tests was used to calibrate the transient model.

Figure 5 summarizes the results of the hydrogeological and geochemical models as the recovery of the groundwater system to equilibrium after approximately 15 years and the achievement of a steady state in water quality after approximately 10 years. In the two pit lakes that are predicted to evolve at Kintyre, the total dissolved solids (TDS) of pit lake water will reach hypersaline concentrations of between 120,000 mg/L and 150,000 mg/L (Figure 5) and the pH will remain circumneutral to slightly alkaline.

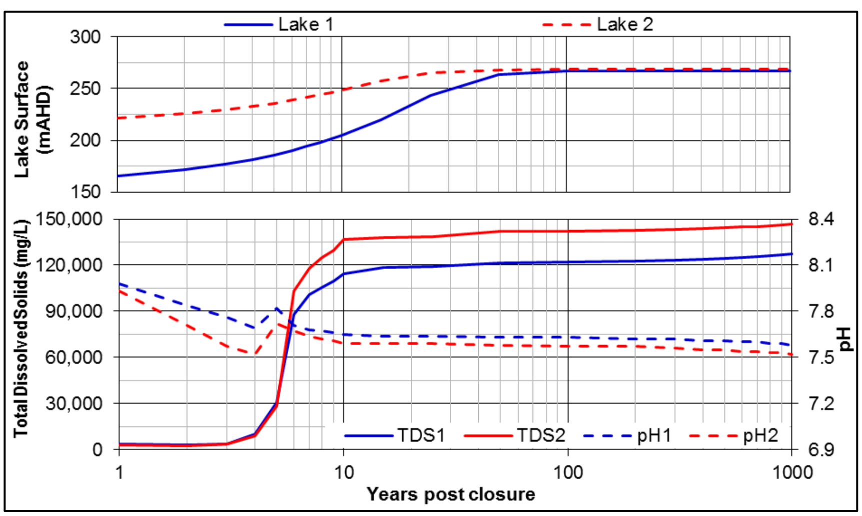

Figure 5 Pit lake level recovery with TDS and pH

Figure 6 shows the maximum extent of the salinity plume in the horizontal direction (from model layer 8 in the bedrock) for the constant-density case after 100 years. Contour intervals in Figures 6 through 9 are

1, 10, and 100 kg/m³, which are equivalent to 1,000, 10,000, and 100,000 mg/L, respectively. The mean TDS concentration of groundwater at the site is approximately 3,300 mg/L (i.e., brackish) so a minimum TDS contour of 1,000 mg/L was used. In Figure 6, salinity migrates less than 100 m horizontally from the pit lake as a result of dispersion because the pit lakes are terminal sinks.

Figure 8 shows the vertical extent of the salinity plume for the constant-density case through a west-east line indicated on Figure 6, over a distance of approximately 1 km after 100 years. Each model layer is approximately 25 m thick below the pit until a depth of approximately 320 m below ground surface (bgs). The lower model layers after a depth of approximately 320 m bgs are omitted from the vertical extent figures. Gray and blue cells represent no flow and pit lake cells, respectively. The blue and black contours represent the water table and the TDS concentration, respectively. Figure 7 indicates that a salt plume migrates approximately 50 m vertically before being indistinguishable from mean groundwater salinity.

Figures 7 and 9 show the horizontal and vertical extent of the salinity plume for the variable-density case after 100 years. In Figure 7, the horizontal extent is nearly identical to the constant-density case and the salinity plume does not move beyond the surface extent of the pit. In Figure 9, salinity migrates further vertically (approximately an additional 75 m) than the constant density case as a result of pit lake density effects, to a maximum depth of 150 m before it is indistinguishable from the salinity of the groundwater. There is no horizontal migration in the deeper model layers as a result of the low horizontal hydraulic conductivity (0.008 m/d) arising from decreased fracture density and aperture of the metamorphic rock at those depths, and consequently the salinity plume is not predicted to migrate offsite.

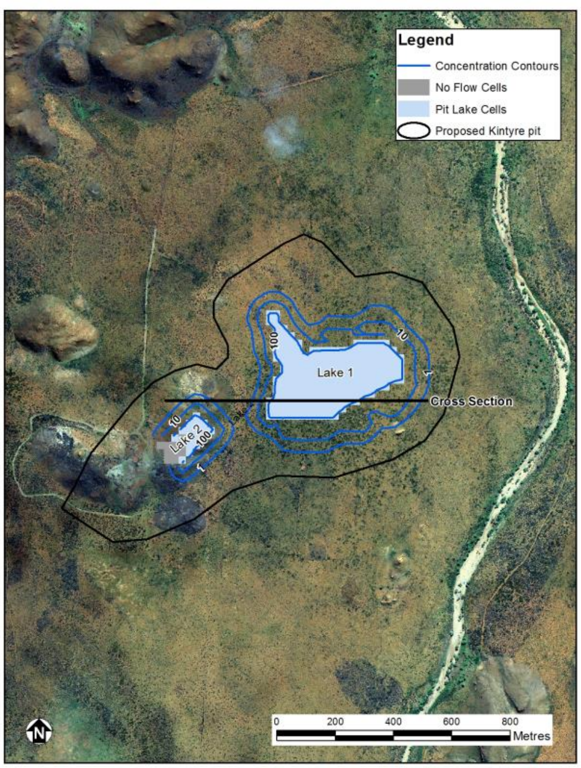

Figure 6 Constant-density salinity contours

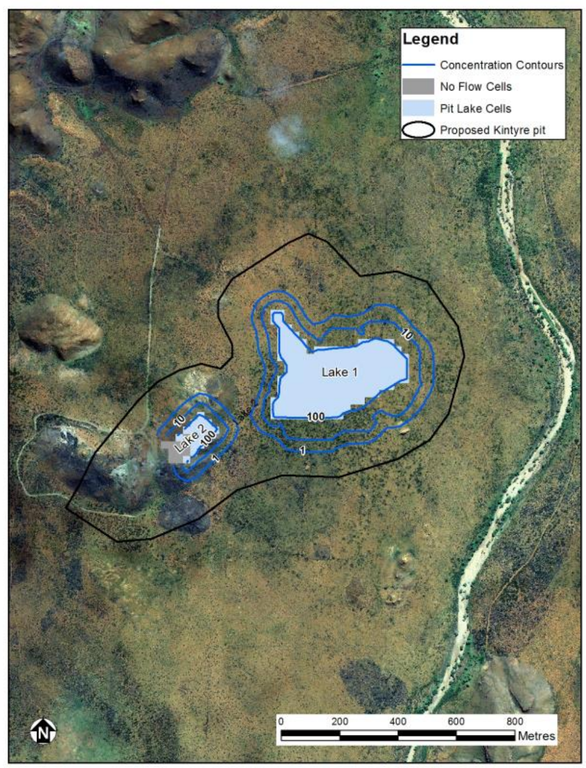

Figure 7 Variable-density salinity contours

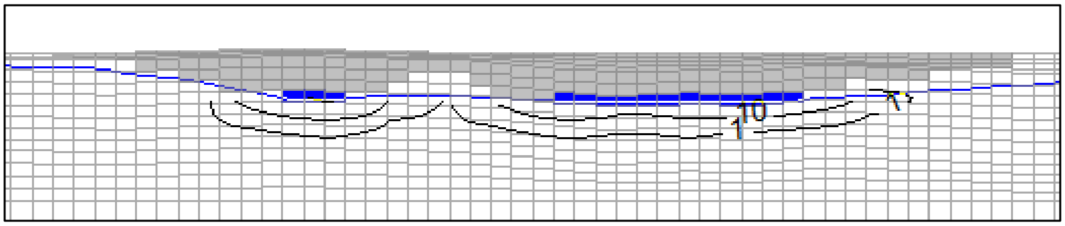

Figure 8 Vertical constant-density salinity contours along cross section from Figure 3. Contour interval is 1, 10, and 100 kg/m³. Vertical grid spacing is 25m below the pit floor.

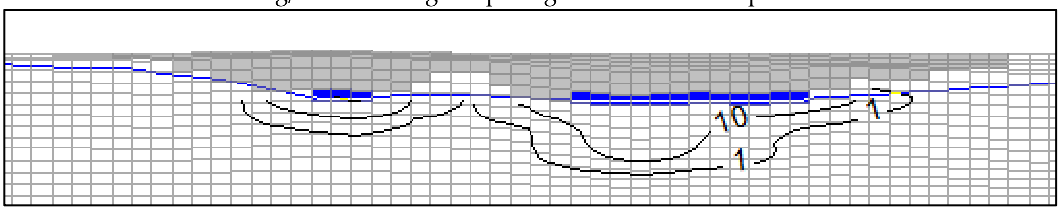

Figure 9 Vertical variable-density salinity contours along cross section from Figure 3. Contour interval is 1, 10, and 100 kg/m³.Vertical grid spacing is 25m below the pit floor.

Given the uncertainty in dispersivity and effective porosity values, three sensitivity simulations were performed to bracket the salinity plumes horizontal and vertical extent:

- Dispersivity factor of four increase [Peclet Number (Pe) = 1];
- Dispersivity factor of 2.5 decrease (Pe = 10); and
- Effective porosity factor of 5 decrease (n = 0.01).

Table 3 provides the change in downgradient distance of the 1,000 mg/L concentration contour for each sensitivity simulation in the horizontal and vertical directions when compared to the variable-density case. Results show that increasing dispersivity could causes the 1,000 mg/L contour to reach the surficial pit shell boundary, but does not leave the site.

Table 3 Variable-density model sensitivity analysis results

Simulation	Horizontal Distance Change (m)	Vertical Distance Change (m)
Dispersivity factor increased (Pe = 1)	+100	+50
Dispersivity factor decreased (Pe = 10)	-25	-30
Effective porosity decreased (n = 0.01)	~0	~0

CONCLUSION

Detailed numerical analyses were conducted to assess if a salt plume originating from the Kintyre pit lakes could migrate offsite toward groundwater receptors. Results show that salinity does migrate horizontally and vertically from the pit lake, but the 1 kg/m³ or 1,000 mg/L TDS contour progresses less than 100 m from the pit lake using base case parameters. Results from this study show that given the low permeability of the bedrock beneath the pit floor, salinity migration from this pit will be limited and will not impact downgradient groundwater dependent ecosystems.

ACKNOWLEDGEMENTS

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NOMENCLATURE

bgs	below ground surface
mAHD	meters Australian Height Datum
Pe	Peclet Number
TDS	Total Dissolved Solids

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