Appendix B

Simulation of leaching of non-reactive and radionuclide contaminants from proposed Jabiluka silo banks
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Groundwater flow through and past the proposed silos will be nearly horizontal, and to the east. The modelling described in this section was performed to provide estimates of local contaminant concentrations in groundwater near the silos. The results were then used in the regional contaminant transport model to predict the extent of movement of contaminants towards Swift Creek.

The regional Monte-Carlo analytical solute transport model is presented in Appendix A.

The model described here examines the interaction of groundwater flow between the silo tailings paste and the Kombolgie Formation fractured sandstone and determines the mobility of both non-reactive and reactive contaminants.

For these series of simulations a 3D saturated/unsaturated flow and solute transport model code MODFLOW-SURFACT (MS)\(^1\) was used. MS is an enhanced and much advanced version of the standard USGS MODFLOW saturated groundwater flow code. MS uses a Total Variation Diminishing (TVD) van Leer flux limiting solution scheme for the solute transport equation producing very accurate mass balance results. MS includes linear and non-linear adsorption isotherms, 1\(^{st}\) order decay processes (radioactive/biological) and multi-species contaminants with daughter decay simulation if required.

Groundwater flow and a single silo

The MS code was set up to examine the leaching characteristics of a single silo repository. For these simulations a finite difference mesh of cells, each 1 m x 1 m in dimension were used representing a 2D one metre thick single horizontal layer through the silo. A steady state hydraulic gradient of 0.03 was used for all simulations under complete saturated flow conditions. For a single silo the model has dimensions 100 m x 50 m in the x and y directions respectively with the gradient in the x direction. Constant heads were applied at each end of the model to achieve the required gradient.

A gradient of 0.03 was selected as this is approximately the hydraulic gradient within the proposed silo bank area based on data provided by ERA.

Figures B1 and B2 present part of the hydraulic head contours and velocity vector magnitudes around a simulated single silo for ratios of aquifer permeability (Ka) to silo tailings paste permeability (Ks) of 10 and 1000. Note that the figures show only 36 m of the full 50 m model width.

Each contour in these figures represents a 0.1 m increment in the hydraulic head.

As would be expected, although some groundwater flow is directed into the silo, as the permeability ratio Ka/Ks increases flow around the edges of the silo\(^2\) dominates.

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\(^1\) The program was developed by Hydrogeologic Ltd in the US, is internationally recognised and has been used to simulate high and low level radioactive waste sites in that country.

\(^2\) The pattern of the flow is dimensionless in this case and depends only on the permeability ratios and not the absolute values of permeability of the aquifer or silo paste.
Non-reactive contaminant movement

Single silo
Under the groundwater flow conditions described above, two scenarios were examined: the first for an aquifer permeability $K_a = 0.01$ m/day and paste permeability $K_s = 10^{-4}$ m/day (ratio $K_a/K_s = 100$); the second for $K_a = 0.01$ m/day and $K_s = 10^{-5}$ m/day (ratio $K_a/K_s = 1000$).

Dispersivity values adopted in the fractured sandstone for all simulations were longitudinal dispersivity $\alpha_L = 1.0$ m; transverse dispersivity $\alpha_T = 0.1$ m and vertical dispersivity $\alpha_V = 0$ m. For the tailings paste the values adopted were longitudinal dispersivity $\alpha_L = 0.1$ m; transverse dispersivity $\alpha_T = 0.01$ m and vertical dispersivity $\alpha_V = 0$ m.

Porosity was set in the aquifer at a conservative 5% ($Pa = 5\%$) and in the silo at 10% ($Ps = 10\%$). Using 5% is conservative for the near field simulations since it will increase the source concentrations somewhat relative to simulations conducted at lower effective porosity values. Note however that porosity is not a sensitive parameter for concentrations near the source. Sensitivity runs indicate that a decrease of porosity from 0.05 to 0.01 will only decrease the concentrations near the source by about 10%.

The simulation was run over a period of 200 years.

The results are presented in figures B-3a, b, c and B-4a, b and c. In each case (a) is a plan view of percentage normalized contaminant concentrations $C/Co \times 100$, (b) is a longitudinal profile through the center of the silo in the direction of flow showing the percentage normalized concentrations, and (c) is a profile at right angles to the flow direction 2 m from the down-gradient edge of the silo showing percentage normalized concentrations. Note that the plot minimum concentration (dark blue) was set at 0.1%.

In figures B-3a, b, c a plume emanates from the silo but the maximum concentration near to the source (2 m down-gradient from the edge of the silo) is less than 10% of the source concentration, decreasing to less than 5% at 100 m down gradient.

For figures B-4a, b, c with a paste permeability of $10^{-5}$ m/day, the near source concentration is less than 2% of the source values.\(^3\)

Series of silos
In order to determine the effect of a series of silos on the concentration distribution, four silos\(^4\) were examined using a model with adjacent boundaries taken along two longitudinal planes of flow symmetry. Silos were positioned with their centers 30 m apart\(^5\). This section would be representative of a 30 m wide part of the continuous double row of silos. For a group of silos the model dimensions are 100 m x 30 m in the x and y directions respectively with the gradient in the x direction.

The concentration distributions after a 200 year period for permeability ratios of 100 ($K_a = 0.01$ m/d, $K_s = 10^{-4}$ m/day) and 1000 ($K_a = 0.01$ m/day, $K_s = 10^{-5}$ m/day) are shown in figures B-5a, b, c and B-6a, b, c respectively.

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\(^3\) As an hypothetical example in this case: if the source were sulphate at 20 000 mg/L then at 2 m the concentration would be 2% of 20 000 mg/L or 400 mg/L.

\(^4\) The scope, budget and timing for the current report does not permit simulation of the entire series of silos proposed.

\(^5\) Data provided by ERA Jan 1999
In these cases concentrations in a longitudinal profile along one of the symmetry planes through the center of the silos (top or bottom profiles yield the same values) were plotted. They were also plotted for a section at right angles, two metres down-gradient from the edges of the silos.

For the first case, the downstream concentrations reach a maximum of 12% of the source concentrations whilst in the second case they reach a maximum of 3%.

**Reactive contaminant movement**

**Series of silos**

**Uranium**

Uranium movement was simulated near field (2 m down-gradient from silos) over a 1000 year period, using a distribution co-efficient Kd of 1 mL/g (conservative retardation factor of 21) and a permeability ratio between tailings paste and aquifer permeability of 100 (Ka = 0.01 m/day and Ks = 0.0001 m/day). The results are presented in figures B-7a, b and c. Note that the same retardation was applied to the tailings paste.

The results indicate maximum concentrations of 18% near the source.

**Radium 226**

Figures B-8a, b, c present the concentration distribution near field results for Radium 226 after 1000 years for a permeability ratio of 100 (Ka = 0.01 m/day and Ks = 10^{-4} m/day and a distribution co-efficient of 5 mL/g (conservative retardation factor 101).

The results show effective immobilisation for the permeabilities and retardation factor considered. The plot of concentrations through the silos show a decrease in the maximum concentration due to decay of radium 226 during the 1000 year period (radium 226 half life 1600 yrs) and about 5% concentration at 2 m from source.

Also simulated was the case where the source radium 226 concentration stays constant as a result of thorium decay. That is, it was assumed that the radium 226 derived from thorium 230 decay would be sufficient to replace the decayed radium at the source over 1000 years. These results showed only a relatively small increase in the maximum concentration 2 m down gradient from the source from the previous 5% to a value of 6%.

**Effect of single major fault/fracture system**

The effect of a single fault /fracture system within the aquifer between two silos (but not through them) was also examined. Note that it can be assumed that in the case of discovery of a geological feature of this type running through a proposed silo site, the site would not be utilised or the fissure would be grouted to prevent groundwater flow along it.

The fault is assumed to be 2 m wide (1 m each side of the plane of symmetry) and to have a permeability of 0.5 m/day (fig 9). Two cases were simulated. The first is a repeat of the case of a non-reactive contaminant given in figures B-3a, b, c, but with included fault, over a period of 200 years, and the second of the case given in figures B-7a, b, c for uranium, but with a fault included, over a period of 1000 years.

Parameters for these cases are those used previously except that the fault zone was also assigned a longitudinal dispersivity of 1 m and a transverse value of 0.1 m and vertical 0 m.

The results for each of these cases are shown in figures B-10a, b, c and figures B-11a, b, c respectively.
For the 200-year simulation comparison made between the cases with and without a fault zone indicate that the concentrations are less with the fault zone than without it in the near field. It would appear that higher velocities in the fault zone remove solute mass more rapidly, but because silo mass flux is rate-limited (i.e., the silo cannot supply sufficient mass) the concentration is lower in the fault zone in this case.

For the 1000 year simulation the effect of the fault is to cause increased leaching which reduces the concentrations in the silos to less than 5–10% with very low concentrations in a down gradient direction after this time.

**Leaching rate – non-reactive contaminant**

The source leaching rate for a non-reactive contaminant was determined using the case depicted in figure B-5a over a period of 1000 years. To determine this rate, concentrations were calculated 2 m down-gradient from the set of silos and a curve fitted to the numerical model data.

The results indicate a leaching decay constant $\gamma$ of $4 \times 10^{-6}$ day$^{-1}$. Thus the source decay by leaching is given by:

$$C = C_0 e^{-0.000004 t}$$

where $C$ is the concentration at the ‘source’; $C_0$ the initial concentration at the ‘source’, and $t$ the time in days. This constant has been used in the analytical model described in Appendix A.

Note that this constant only applies to the assumed hydrogeological conditions at the site.

**Non-reactive contaminant movement – higher paste permeability**

The final simulation examines the case presented in figures B-3a,b,c but with a tailings paste permeability of $10^{-3}$ m/day. The results are presented in figures B-12a, b and c and indicate severe leaching of the contaminant over the 200-year period.

**Mine void fill**

The mine void fill tailings paste will respond in a similar manner to the single silo, but at a larger scale. Estimates made of the likely relative concentrations immediately down-gradient of the fill for a non-reactive contaminant are given in table B-1.

It is recommended that a more complete numerical simulation of the mine void fill be set up to reproduce as far as possible the actual site conditions to verify the above estimates.

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6 The ‘source’ in this instance is the concentration at 2 m, not the concentration in the silo.
<table>
<thead>
<tr>
<th>Tailings Paste Permeability m/day</th>
<th>Relative Concentration %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^5$</td>
<td>&lt;5</td>
</tr>
<tr>
<td>$10^4$</td>
<td>&lt;30</td>
</tr>
<tr>
<td>$10^3$</td>
<td>80-90</td>
</tr>
</tbody>
</table>

Table B-1  Tailings paste permeability and immediate down-gradient Relative Concentration % Non-Reactive Contaminant in Mine Fill Void
Appendix B Figures

Note:
All grid dimensions in the figures which show plan views of the finite difference grid used in the silo leaching model (fig B-1a, B2a,…B12a) are in metres. Each grid square is 1 m x 1 m.
FIGURE B-1
Jabiluka Review - Groundwater Hydrology
Silo/Aquifer Head and Velocity Vectors
Ks = 0.001 (m/d); Ka=0.01 (m/d) - Gradient 0.03 - Steady State
FIGURE B-2

Jabiluka Review - Groundwater Hydrology

Silo/Aquifer Head and Velocity Vectors

$K_s = 1 \times 10^{-5} \text{ (m/d)}$; $K_a=0.01 \text{ (m/d)}$ - Gradient 0.03 - Steady State
FIGURE B-3a
Jabiluka Review - Groundwater Hydrology
Silo/Aquifer Concentration % - non-reactive contaminant
Ks = 1e-4 (m/d); Ka=0.01 (m/d) - Gradient 0.03 - Pa=5%; Ps=10%; 200 yrs
Figure B-3b - Concentration % Profile - Row 25 - non-reactive - 200 yrs

Kalf and Associates '99
Figure B-3c - Concentration % Profile - Col 36 - non-reactive - 200 yrs

Kalf and Associates 99
FIGURE B-4a
Jabiluka Tech Review - Groundwater Hydrology
Silo/Aquifer Concentration % -non-reactive contaminant
Ks = 1e-5 (m/d); Ka=0.01 (m/d) - Gradient 0.03 -Pa=5%;Ps=10%; 200 yrs
Figure B-4b  Concentration % Profile  -Row 25 - non-reactive -200 yrs

Kalf and Associates 99
Figure B-4c Concentration % Profile - Col 36 - non-reactive - 200 yrs

Kalf and Associates 99
FIGURE B-5a
Jabiluka Review - Groundwater Hydrology
Silo/Aquifer Concentration % - non-reactive contaminant
Ks = 1e-4 (m/d); Ka = 0.01 (m/d) - Gradient 0.03-Pa=5%;Ps=10%-200 Years
Figure B-5b Concentration % Profile - Row 1 - non-reactive - 200 yrs
Figure B-5c Concentration % Profile - non-reactive - Col 66- 200 yrs

- Layer 1
FIGURE B-6a
Jabiluka Review - Groundwater Hydrology
Silo/Aquifer Concentration % - non-reactive contaminant
Ks = 1e-5 (m/d); Ka=0.01 (m/d) - Gradient 0.03-Pa=5%;Ps=10%-200 Years
Figure B-6b Concentration % Profile - Row 1 - non-reactive - 200 yrs

Kalf and Associates 99
Figure B-6c Concentration % Profile - Col 66 - non-reactive - 200 yrs

Kalf and Associates 99
FIGURE B-7a
Jabiluka Review - Groundwater Hydrology
Silo/Aquifer Concentration % - Uranium
Ks = 1e-4 (m/d); Ka=0.01 (m/d) - Gradient 0.03 - Pa=5%;Ps=10% - 1000 Yrs; Rf=21
Figure B-7b Concentration % Profile - Row 1 - Uranium - 1000 yrs - Rf=21

Kalf and Associates 99
FIGURE B-8a
Jabiluka Review - Groundwater Hydrology
Silo/Aquifer Concentration % - Radium 226
Ks = 1e-4 (m/d); Ka=0.01 (m/d) - Gradient 0.03 - Pa=5%;Ps=10% - 1000 Yrs; Rf=200a;100s
Figure B-8b Concentration % Profile - Row 1 - Radium 226-1000 yrs; Rf=201a, 101s

Kalf and Associates 99
Figure B-8c Concentration % Profile - Col 66 - Radium 226 - 1000 yrs-Rf=201a,101s
FIGURE B-9
Jabiluka Technical Review
Groundwater Hydrology
Assumed Fault/Fracture Zone

Kaff and Associates 99
FIGURE B-10a
Jabiluka Review - Groundwater Hydrology
Silo/Aquifer Concentration % - non-reactive contaminant
Ks = 1e-4 (m/d); Ka=0.01 (m/d) - Gradient 0.03 - Pa=5%; Ps=10% - 200 Yrs - Fault Kf=0.5 m/day
Figure B-10b Concentration % Profile - Row 1- non-reactive-200 yrs with Fault
Figure B-10c Concentration % Profile - Col 66- non-reactive-200 yrs with Fault
Figure B-10d Concentration % Profile - Row 30 - non-reactive-200 yrs fault opposite

[Graph showing concentration profile across distance]
FIGURE B-11a
Jabiluka Review - Groundwater Hydrology
Silo/Aquifer Concentration % - Uranium
Ks = 1e-4 (m/d); Ka=0.01 (m/d) - Gradient 0.03 - Pa=5%;Ps=10% - 1000 Yrs-Fault Kf=0.5 m/day; Rf=21
Figure B-11b Concentration % Profile - Row 1 - Uranium - 1000 yrs with Fault
Figure B-11c  Concentration % Profile - Col 66-Uranium-1000 yrs with fault
Figure B-11d Concentration % Profile - Row 30 - Uranium - 1000yrs with Fault
FIGURE B-12a
Jabiluka Review - Groundwater Hydrology
Silo/Aquifer Concentration % - non-reactive contaminant
Ks = 1e-3 (m/d); Ka=0.01 (m/d) - Gradient 0.03-Pa=5%;Ps=10%-200 Years
Figure B-12b Concentration % Profile - Row 1 - non-reactive - 200 yrs

[Graph showing concentration profile with peak at around 60-70 distance (m)]

Kalf and Associates 99
Figure B-12c Concentration % Profile - Col 66 - non-reactive - 200 yrs

Kalf and Associates 99