11 Summary and discussion of results

11.1 General comments

Conservative estimates of Jabiluka tailings paste properties based on measured properties of tailings produced from very similar ore at Ranger and data from the literature can be used to convert the proportional (dimensionless) contaminant concentration figures determined by modelling to conservative estimates of actual concentrations. In the following discussion, such values have been introduced where relevant.

The conservative value used for expected paste permeability is 10^{-4} m/day, although it should be possible to achieve 10^{-5} m/day. Poor placement techniques in backfilling mine voids might possibly increase the effective bulk permeability to 10^{-3} m/day so this figure has also been introduced to demonstrate the consequences if this were to happen.

Maximum tailings pore water concentrations of the four potential contaminants which have been studied in this investigation are estimated from Ranger tailings data to be:

sulphate	20 000 mg/L
magnesium	5 000 mg/L
manganese	500 mg/L
uranium	15 Bq/L
radium	15 Bq/L

Reduced concentrations at selected distances east of the silos and west of the mine backfill can be estimated by applying the ratios and percentages shown in the graphs to the source concentrations given above.

11.2 Discussion of specific findings

Numerical model simulations conducted to determine leaching behaviour over time of an individual silo and a group of silos (Appendix B) indicate that it would be desirable to achieve a target paste permeability of 10^{-5} m/day if possible, and not to exceed a permeability of 10^{-4} m/day. Simulations show that with a paste permeability of 10^{-4} m/day leaching of non-reactive contaminants would create a concentration generally less than 12% of the source concentration immediately down-gradient of the silos. Dispersion would reduce this concentration further in a down-gradient direction.

Preliminary calculations of the leaching concentrations from the mine void fill indicate that concentrations immediately down-gradient of the source would most likely be less than 5% of the source concentration for a paste permeability of 10^{-5} m/day and less than 30% for a paste permeability of 10^{-4} m/day. For a paste permeability of 10^{-3} m/day, the immediate down-gradient concentrations could be 80% or more.

Analysis conducted using a finite element section flow model, combined with Monte Carlo simulations using numerical and analytical solute transport models has provided estimates of normalised concentrations with respect to distance, for possible ranges of key aquifer and contaminant parameter values. The flow model confirms that possible pathways around or through the tailings filled orebody void will be directed towards the bedrock beneath the Magela floodplain to the west whilst flow around and through the silo bank will follow an easterly course. The model indicates essentially horizontal flow with a slight upward component through the underlying bedrock.

The modelling results show that over a period of 200 years the non-reactive contaminant fronts from the silos would migrate a probable distance of less than 200 m in a easterly direction. Beyond this distance concentrations would be negligible. The maximum computed distance (of very low probability) for this case is 800 m.

The simulations conducted for uranium over a period of 1000 years indicate that contaminant fronts from the silos with a paste permeability of 10^{-4} m/day would migrate a probable distance of less than 50 m in an easterly direction. The maximum computed distance (of very low probability) for this case is less than 300 m. For the same period, the radium 226 fronts from the mine void fill would migrate a probable distance of less than 15 m in a easterly direction with a maximum distance (of very low probability) of less than 100 m.

Simulations conducted for a non-reactive contaminant emanating from the mine fill void indicates a probable contaminant migration distance in a westerly direction of 500 m after 200 years although greater migration distances are possible. However, the large migration distances indicated in the Monte Carlo simulations can largely be ignored because the gradients beneath the Magela floodplain would be much smaller than those assumed in the simulations. The groundwater would also be entering an area of already poor water quality so would not have a significantly deleterious effect on the environment.

For the silos with a paste permeability of 10^{-4} m/day, uranium migration (to negligible concentrations) could extend a probable distance of 200 m in a westerly direction over a period of 1000 years. The maximum computed distance (of very low probability) for negligible concentrations in this case is 1200 m. For the same period the radium 226 concentration fronts from the mine void fill would migrate a probable distance of less than 50 m in a westerly direction. A maximum migration distance to negligible concentrations (of very low probability) of 500 m is indicated.

Based on the results of leaching and dispersion-advection simulations it is evident that sulphate will be the most mobile of all potential contaminants. Also it is evident that for the most probable situation over 200 years, concentrations will decrease to negligible concentrations over a distance of 200 m. For example, should the concentration of sulphate in the silo be 20 000 mg/L, the concentrations immediately down-gradient of the silo would be less than 10% (or less than 2000 mg/L) and at 100 m the concentration would be a further 1% of this value (ie 20 mg/L). Concentrations of sulphate as well as being affected by dispersion will also be affected by dilution due to the influence of rainfall infiltration at shallow depths. Hence there would be a further dilution for that part of the plume extending upward into shallow alluvial or weathered rock aquifers. Overall, our conclusion is that there would be negligible potential for contamination of surface streams to the east. The probability of a continuous high permeability fracture system extending to the east over long distances is considered to be low. Even with a fracture system extending some one to two hundred metres, the final concentration due to both dispersion and dilution would be low and probably negligible compared to the high sulphate levels in the Magela floodplain created by natural oxidation processes. Similar arguments are valid for concentrations extending in a westerly direction from the mine filled void provided an adequately low bulk permeability (10^{-4} m/day or preferably less) for the mine void tailings paste can be achieved. However, we recommend that further complete numerical solute transport simulations be conducted for both the entire silo bank and mine void fill to confirm these predictions.

12 Potential for contamination of the wetlands

The results of the simulations conducted, based on the assumptions made and data available, indicate that if a low permeability of the proposed tailings paste material can be achieved, it will reduce significantly the rate at which the available contaminant mass will leach from the repositories.

Simulations conducted for radionuclides uranium and radium 226 indicate that these contaminants are restricted in their movement and provided that adequate low permeability can be achieved in the tailings paste the concentrations will remain at background levels within the wetlands. This situation would also apply to manganese.

Sulphate will be the most mobile contaminant but concentrations emanating from the tailings paste by flowing groundwater would be reduced significantly provided tailings paste permeability is equal to or preferably lower than 10^{-4} m/day. Sulphate concentrations in the wetlands currently occur at high levels due to naturally occurring processes of oxidation of pyrite from the bedrock. Whilst the possibility exists of some sulphate reaching the floodplain to the west over a 200 year period the concentration levels could be expected to be below those that currently occur naturally in this area.

It is significant that sulphate levels in the Magela floodplain are substantially reduced by Wet season floodwaters through dilution.

The probability of occurrence of linear and continuous major fracture systems extending for kilometres is unlikely, and it is not considered that these structures would be sufficiently continuous to propagate contaminants beyond distances computed in this analysis.

13 Conclusions

1. Good quality groundwater occurs in the vicinity of the proposed Jabiluka minesite within fractured bedrock comprising Kombolgie Formation siliceous sandstone and Cahill Formation schists and carbonates, a weathered profile of variable thickness and sandy deposits elsewhere along drainage gullies. Poor quality groundwater occurs in organic silts, clays and sand across the Magela Creek floodplain.

2. Groundwater flow is controlled by topography and flows towards the east and west from the catchment divide formed by an approximate north-south ridge of Kombolgie sandstone which overlies the eastern edge of the Jabiluka orebody No 2. On the eastern side of the divide groundwater flows towards Swift Creek and then north to the Magela floodplain. On the western side of the divide groundwater flows directly towards the main branch of the Magela floodplain. Groundwater generally flows with higher velocity through the non-indurated sediments and weathered profile than the underlying fractured bedrock. The rock mass of schist and carbonate west of the orebody in the mine valley has overall higher permeability than the sandstone to the east. Hence, groundwater velocities would tend to be higher in a westerly direction than in an easterly direction by, on average, one order of magnitude. Beneath the floodplain, particularly during the Wet season, groundwater velocities could be expected to be low due to the low hydraulic gradients that would occur in a northerly direction. It is possible, although not certain, that a reverse hydraulic gradient is established at the edge of the floodplain towards the mine site during Wet seasons.

3. Groundwater quality at Jabiluka can be separated into two distinct groups. The first group includes groundwater within the bedrock and overlying weathered zone beneath and

immediately adjacent of the ridge. The second group includes groundwater beneath the Magela floodplain. The first group is characterised by low salinity, having very low to low chloride, sulphate, silica and neutral to slightly alkaline pH with no major change in the chemical characteristics noted between the underlying Kombolgie and Cahill formation groundwater. The second group is characterised by having overall higher overall ionic content, high sulphate and iron and low pH. Overall concentrations of naturally occurring radionuclides is low. The chemical differences between the two groups can be largely attributed to flushing action through Wet season recharge along the topographic ridge and the relatively inert sandstone leading to waters of the first group. The decay of organic matter, oxidation of pyrite leading to high sulphate concentrations and seasonal floodwater fluctuations along the floodplain is thought to be responsible for the chemical characteristics of the second group. The occurrence of low concentrations of radionuclides in the groundwater compared with other sites elsewhere in Australia and the US is probably also due to Wet season groundwater dilution compared to arid climates at these other sites.

4. Overall the concept of tailings paste disposal at depth is a good one. However, there is currently little information available on the leaching characteristics of the proposed tailings paste disposal technology. This includes the ultimate permeability, curing characteristics under saturated conditions and release rates of the potential contaminants from the paste material. Consequently, it is not possible at this stage to verify the magnitude of absolute concentrations that would emanate from either the mining void tailings fill or bank of proposed disposal silos. However, it is possible to determine the range of normalised concentrations, that is, fractions or percentages of the source concentration (whatever they may be) with distance from these sources. Using these results it would be possible to determine absolute concentrations when the source concentrations are known from these facilities or when they can be determined with greater confidence. At this time the best estimates of Jabiluka tailings paste properties can be derived from the results of tests on Ranger mine tailings adjusted for the effects of partial dewatering and addition of cement during paste production. They have been taken into account when selecting conservative values of parameters for modelling contaminant movement.

5. Numerical model simulations were conducted to determine leaching behaviour over time of individual and a group of silos, using conservative estimates of aquifer permeability. These simulations (Appendix B) indicate that it would be desirable to achieve a target paste permeability of 10^{-5} m/day if possible, and not to exceed a permeability of 10^{-4} m/day. This maximum would be similar to the permeablity required for a clay liner in a landfill (ie 10^{-9} m/sec) and should be achievable. Simulations show that with a paste permeability of 10^{-4} m/day leaching of non-reactive contaminants would create a concentration generally less than 10% of the source concentration immediately down-gradient of the silos. Dispersion and dilution will reduce this concentration further in a down-gradient direction to an extent demonstrated by the regional scale modelling summarised below.

6. Preliminary calculations on the leaching concentrations from the mine void fill indicate that concentrations immediately down-gradient of the source would most likely be less than 5% for a paste permeability of 10^{-5} m/day and 30% of the source concentration for a paste permeability of 10^{-4} m/day. However, for a paste permeability of 10^{-3} m/day the immediate down-gradient concentrations could be 80% or more.

7. An analysis conducted using a finite element section flow model, combined with Monte Carlo simulations using analytical solute transport models has provided estimates of

normalised concentrations with respect to distance, for possible ranges in key aquifer and contaminant parameter values. The flow model confirms that possible pathways around or through the tailings filled orebody void will be potentially directed towards the bedrock beneath the Magela floodplain to the west whilst those through the silo bank will follow a potential westerly course. The model indicates essentially horizontal flow with a slight upward component through the underlying bedrock for the western flow path.

8. The modelling results show that over a period of 200 years the non-reactive contaminant fronts from the silos would migrate a probable distance of less than 200 m in a easterly direction to negligible concentrations. The maximum computed distance (of very low probability) for this case is 800 m.

9. The simulations conducted for uranium over a period of 1000 years indicate contaminant fronts from the silos with a paste permeability of 10^{-4} m/day would migrate a probable distance of less than 50 m in an easterly direction to negligible concentrations. The maximum computed distance (of very low probability) for this case is less than 300 m. For the same period the radium 226 fronts from the mine void fill would migrate a probable distance of less than 15 m in a easterly direction to negligible concentrations with a maximum distance (of very low probability) of less than 100 m.

10. Simulations conducted for a non-reactive contaminant emanating from the mine fill void indicates a probable contaminant migration distance in a westerly direction of 500 m after 200 years although greater migration distances are shown to be possible for the assumed conditions. However, it is considered that the larger migration distances indicated in the simulations can be ignored because the gradients beneath the Magela floodplain would be much smaller than those assumed in the simulations.

11. For silo fill with a paste permeability of 10^{-4} m/day, uranium migration (to negligible concentrations) could extend a probable distance of 200 m in a westerly direction over a period of 1000 years. The maximum computed distance (of very low probability) for negligible concentrations in this case is 1200 m. For the same period the radium 226 concentration fronts from the mine void fill would migrate a probable distance of less than 50 m in a westerly direction to negligible concentrations. A maximum migration distance to negligible concentrations (of very low probability) of 500 m is indicated.

12. Based on the results of leaching and dispersion-advection simulations it is evident that sulphate will be the most mobile of all potential contaminants. Also it is evident that for the most probable situation over 200 years concentrations will decrease to negligible concentrations over a distance of 200 m. For example should the concentration of sulphate in the silo be 20 000 mg/L then the concentrations immediately down-gradient of the silo would be less than 10% (or less than 2000 mg/L) and at 100 m the concentration would be a further 1% of this value (ie 20 mg/L). Concentrations of sulphate as well as being affected by dispersion will also be affected by dilution due to the influence of rainfall infiltration at shallow depth. Hence there would be further dilution for that part of the plume extending upward to shallow depth. Overall our conclusion is that there would be negligible potential for contamination of surface streams to the east. The probability of a continuous high permeability fracture system extending to the east over long distances is considered to be low. Even with a fracture system extending some one to two hundred metres the final concentration due to both dispersion and dilution would be low and, likely to be at negligible levels, compared to the high sulphate levels in the Magela floodplain created by natural oxidation processes. Similar arguments are valid for concentrations extending in a westerly direction from the mine filled void provided an

adequate low bulk permeability (10^{-4} m/day or preferably less) for the mine void tailings paste can be achieved. However, we recommend that further complete numerical solute transport simulations be conducted of both the entire silo bank and mine void fill to confirm these predictions.

13. Groundwater flow patterns and velocities obtained by modelling indicate that the proposed tailings disposal silos should be sited in Kombolgie sandstone east of the orebody rather than in Cahill formation schist to the west. This would minimise the rate of movement of contaminants leached from the silos toward the Magela floodplain and provide the longest flow path. The sandstone excavated from the silos would also be more resistant to breakdown by weathering than the schist. The silos should be constructed in sandstone which is not significantly weathered. The proposed top level appears to be suitable, but this should be confirmed when the sandstrone is exposed during mining.

14 Recommendations

1. Better and more detailed hydrogeological cross-sections and maps need to be prepared for both the eastern and the western area at Jabiluka. These maps should be drawn accurately to scale and related to mine RL. The maps should show the relationship of the proposed mining stopes, carbonate/schist rocks, locations and depths of bore hydraulic data (projected into the section(s)), position, depth, and dip of known geological structures and weathered zones including the Magela floodplain area.
2. Laboratory permeability and leaching tests of uranium tailings pastes are considered necessary to confirm the validity of property values used in this investigation. Scaled down physical modelling (tank modelling) of accelerated flow around silos containing representative paste tailings would also be useful. The results could be calibrated against a numerical solute transport model to provide additional confidence in the predicted field situation.
3. Additional separate numerical model simulation of the entire silo bank and mine filled void is recommended. This could be initially done using a horizontal planar layer, similar to that described in this report. In due course full 3D models of both flow and solute transport should be used to attempt to reproduce as closely as possible the groundwater flow systems in the area. For example the influence of the pegmatite dyke on contaminant migrations needs to be assessed, in particular whether the dyke could create significant upward flow components into the shallow non-indurated sediments. Additional field test data would be required to set up such a model.