

1 Introduction

1.1 Background

Energy Resources of Australia (ERA) is proposing to mine a uranium deposit at Jabiluka in the Northern Territory, Australia. The proposed Jabiluka mine site is about 230 km east of Darwin and 20 km north of the existing Ranger uranium mine. It is situated within a 73 km² mineral lease near the edge of, but surrounded by, Kakadu National Park (fig 1). The mine will be underground and accessed by a decline from the surface. The area to be occupied by the mine facilities is 27 ha (0.27 km²).

ERA is currently proposing to mine and mill the ore at Jabiluka. This option, known as the Jabiluka Mill Alternative (JMA), will involve storage of mill tailings in deep sub-surface repositories. These repositories are to include the voids created during mining of the orebody and about 180 specially constructed vertical cylindrical silos, 20 m in diameter, up to 135 m long (vertically), situated with their tops about 100 m below ground level.

1.2 Brief and objectives

As a result of the UNESCO World Heritage Committee Delegation to Australia and its recommendations, various aspects of the JMA are to be reviewed by a team of experts. In January 1999 the Supervising Scientist requested specific studies be completed regarding groundwater issues at the site. These issues concern the possible dispersal of contaminants from the proposed buried tailings in the repositories into the surrounding groundwater system. Specifically the issues that needed to be addressed were:

- The likely extent of movement from the tailings repositories of magnesium sulphate, manganese, radium and uranium.
- The effect on contaminant mobility and, as a consequence, on possible surface water contamination, of adding cement to the tailings to form a paste designed to solidify in the repositories.
- Quantification of contaminant concentrations for extreme situations (ie a major fracture or fault intersecting a silo or filled mining stope), and the probability of such a condition.
- Assessment of the effects of spatial location (eg in schist or sandstone) and elevation of tailings storage silos on possible surface water contamination.
- Providing predicted contaminant concentration values for water between the mine and the adjacent Magela floodplain to be used for toxicological risk assessment to be completed by others.

2 Methodology and approach

Given the limited available data and time, the approach used in this report to address these issues has been pragmatic. Where possible, use is made of existing information on aquifer and contaminant characteristics, but where this information is lacking we have used data available in the literature. Both analytical and numerical models have been used in a hybrid approach in conjunction with a stochastic method (Monte Carlo simulation) to determine the leaching characteristics and range of possible contaminant movement, and where possible, we have erred on the side of conservatism.

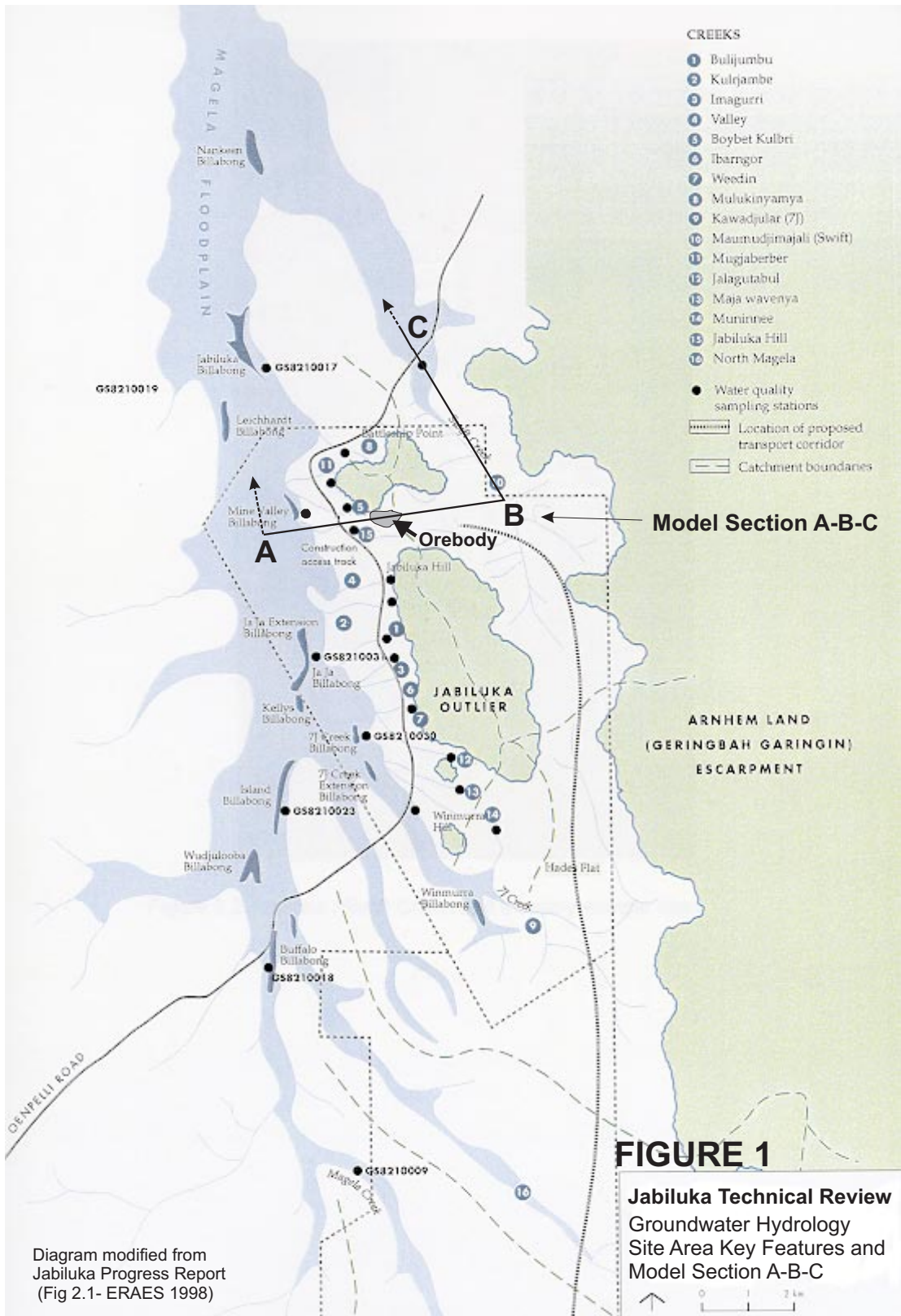


Figure 1 Site area key features and model section A-B-C

Whilst the assessment in this report provides a better understanding of the leaching mechanism and attempts to answer the issues raised, we believe that the material presented can only be considered as a 'first pass'. Thus, this report should therefore be viewed as a screening analysis in its scope. It is clear that more detailed data need to be obtained and, specifically, more complete regional numerical model setups need to be established to reproduce as far as possible the actual field situation both in the entire silo bank area and the tailings filled orebody void.

To verify assumptions that have been made in this report, laboratory and possibly field studies need to be carried out on the physical properties and the adsorption/precipitation and leaching characteristics of the proposed tailings paste material. Paste set, strength, plasticity, porosity, permeability and contaminant fixation/mobility of pastes made from uranium ore tailings need investigation. It is understood that some of this work will be carried out on behalf of ERA in the near future.

Further recommendations on all of these aspects are provided later in the report.

3 Topography, drainage and climate

The Jabiluka mine site is situated in hilly terrain surrounded by undulating to flat terrain along the Magela floodplain with elevations ranging between several metres along the floodplain to 160 m AHD (1160 m Mine RL).¹ The hilly terrain forms an approximate north-south broad ridge which includes the Jabiluka outlier and northern outcrop. The ridge is intersected in an east-west direction by numerous drainage gullies/creeks situated on either side of the topographic divide (fig 1). The top of the orebody is located below a broad, shallow valley, known as Mine Valley, carved from the surrounding quartz sandstone (fig 2). Surface water drainage in Mine Valley is towards the Magela floodplain, which lies about 1.5 km to the west of the topographic divide which separates Mine Valley from the Swift Creek catchment.

On the eastern side of the divide, surface water flows eastward towards Swift Creek which joins the Magela floodplain several kilometres north of the orebody (fig 1).

The region is subject to annual Wet and Dry seasons. It has an average yearly rainfall of about 1500 mm. Monthly average rainfall increases steadily from near zero in September to a peak in January/February (approximately 370 mm in each month) and decreases rapidly to near zero again in June.

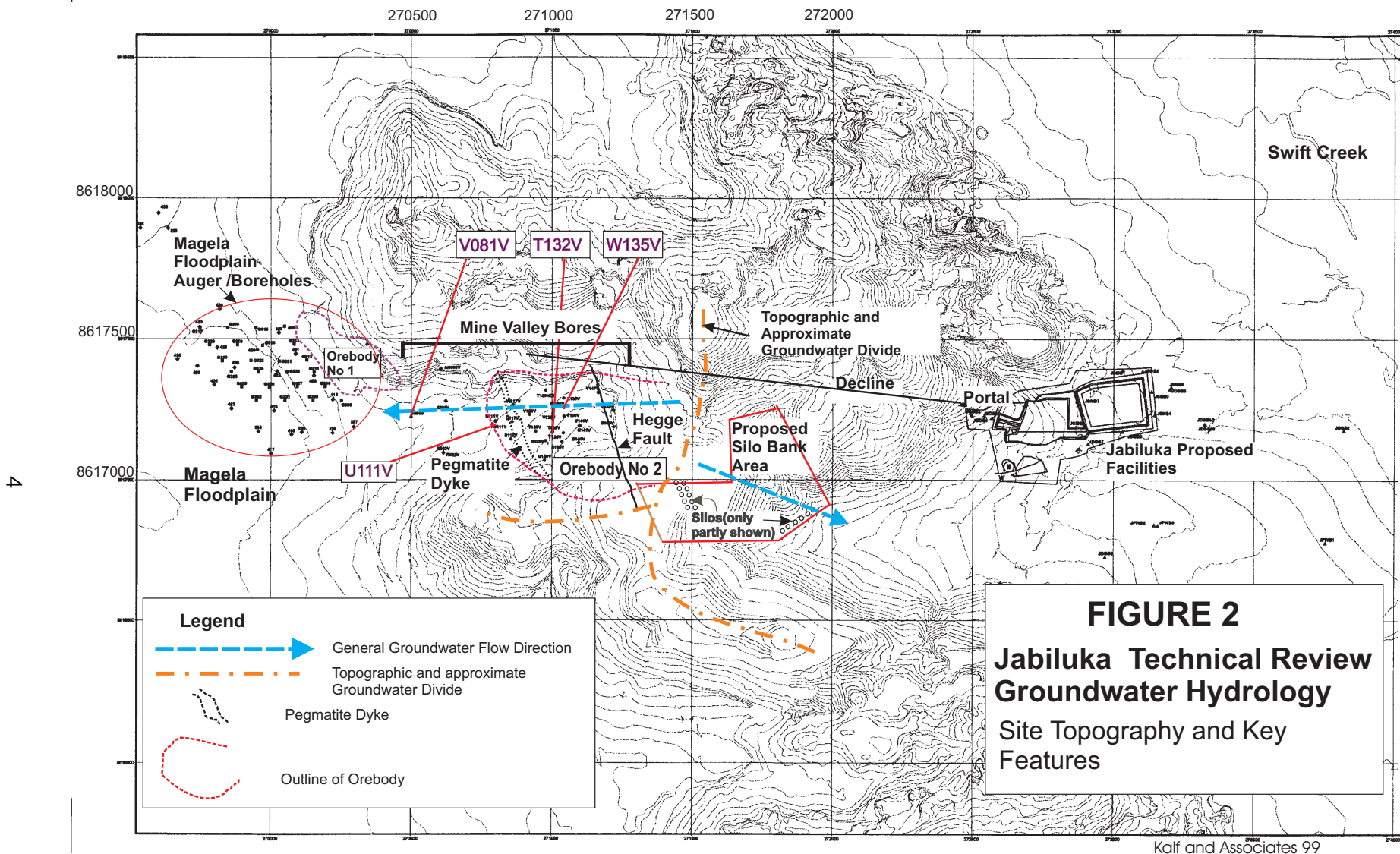
4 Hydrogeology

4.1 Geology

The detailed geology of the area is described in the Jabiluka Project EIS (Kinhill & ERAES 1998).

In summary, the Jabiluka orebody No 2 to be mined is contained within the Cahill Formation which is mostly schist but includes some carbonate. To the west, the Cahill formation underlies the Magela floodplain and forms the bedrock which dips east and south beneath the overlying Kombolgie Formation.

¹ In this report all elevations referred to are Mine RLs unless stated otherwise. Mine RL is obtained by adding 1000 m to the AHD values.



Base Map supplied by ERA Jan 99

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Figure 2 Site topography and key features

The Kombolgie Formation is comprised mainly of quartz sandstone with a little siltstone and forms the broad north-south topographic ridge across the site and terrain further east. Most of the sandstone is better described as quartzite because of the deposition of secondary silica, although some relatively friable layers do occur. The intergranular porosity is very low and the groundwater flow at the mine site is restricted mainly to the joint and fracture system. Inspection of the decline being constructed to gain access to the orebody showed appreciable groundwater inflow only at one fracture zone. Most of the other joints were dry.

Along the Magela floodplain, clays (generally dark organic overlying grey), silts and sandy alluvial sediments overlie the Cahill Formation. The bedrock in contact with the sediments is weathered.

Immediately east and west of the topographic divide the weathered bedrock in the lower drainage valley slopes is overlain by sands and silts. Drilling has revealed that weathered bedrock can occur up to 50 m below ground surface.

Strongly developed lineaments comprising joints/fracture systems in the sandstone are evident from aerial photographs of the Jabiluka outlier and the elevated sandstone outcrop north of orebody No 2. These structures strike at 60 to 80 degrees with another less dominant set at 350 degrees. The structural lineaments are less well defined in Mine Valley; however, it is possible that Mine Valley may have formed along zones of rock weakness created initially in the past by one or a number of these structures that have now been filled in with weathered material.

Other structural features include the Hegge fault that dissects the orebody and a pegmatite dyke that crosses the western part of the orebody (fig 2).

4.2 Groundwater system

4.2.1 Sub-surface water-bearing zones

A hydrogeological section based on that given by Milnes et al (1998) is shown in figure 3. The orientation and extent of this section is given in figure 1 (shown as A-B-C). The section extends from the Magela floodplain in the west across the site through the orebody, the topographic ridge, Swift Creek, and then north until it reaches a branch of the Magela floodplain.

Note that the orebody and tailings silos shown in figure 3 are included to show approximately their locations in the section. The tops of the orebody and silos should not be scaled from the figure. The orebody height varies greatly on either side of the section being used to represent the two dimensional flow and the height drawn is between the upper RL of approximately 958 and lower limits, some undetermined. Under the existing mine plan ore will be extracted down to RL 650 m. The current proposal for the silos is for their tops to be at about the top of the RL 955 mine level so they are shown at approximately RL 960.

There are four main sub-surface water-bearing zones with essentially different hydraulic characteristics within this section at Jabiluka. They include:

- A shallow sandy aquifer overlying weathered bedrock in Mine Valley and east of the topographic divide
- A weathered bedrock aquifer
- A deeper fractured rock aquifer
- Floodplain non-indurated sediments

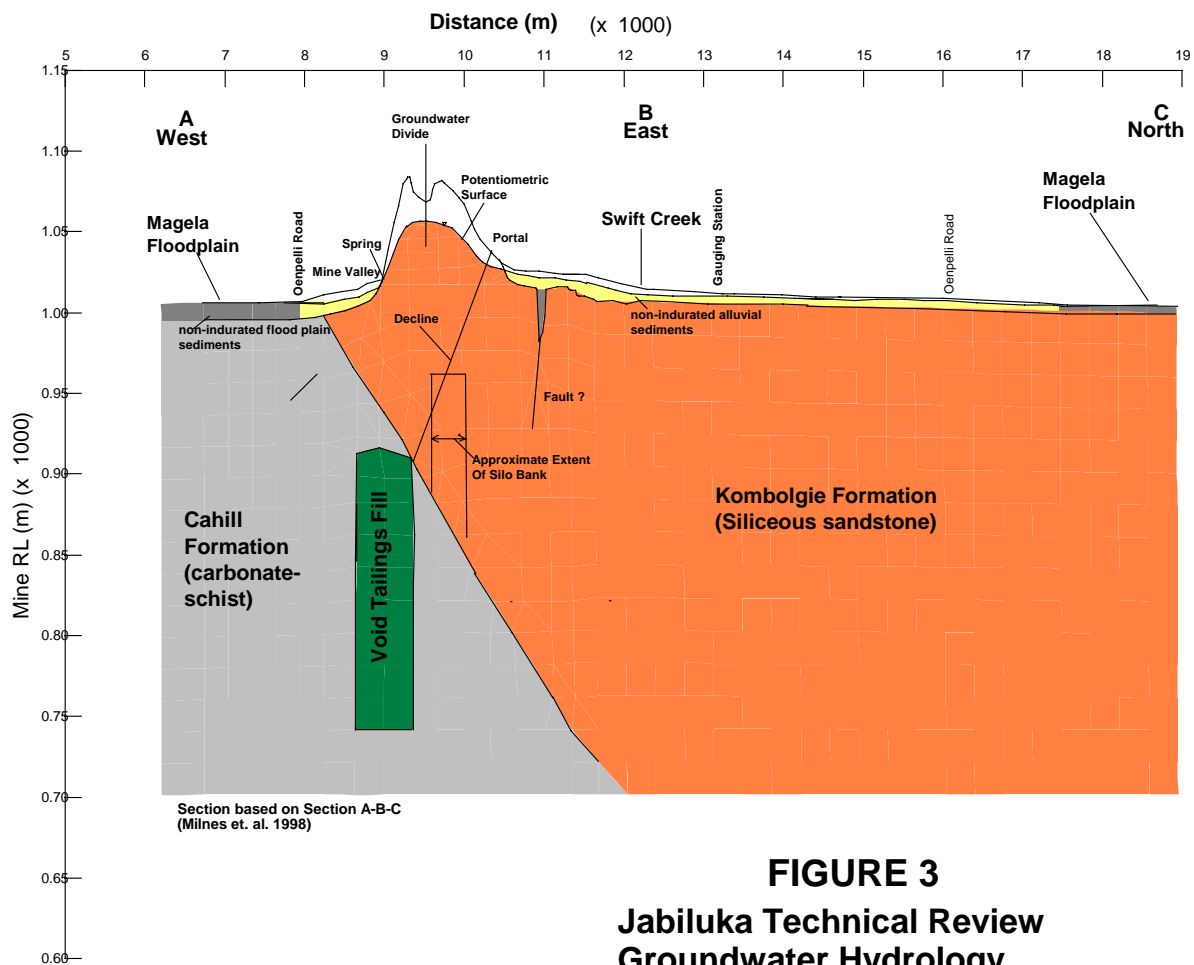


FIGURE 3
Jabiluka Technical Review
Groundwater Hydrology
Model Section A-B-C - Hydrogeological Units
Surface and Sub-surface Features

Kalf and Associates Feb 99

Figure 3 Model section A-B-C – hydrogeological units surface and sub surface features

The shallow aquifer is contained within topographic valley catchments carved into the surrounding Kombolgie Sandstone to the west (ie Mine Valley) and to the east (Swift Creek and its tributaries). According to Foley, this aquifer is comprised of sands and silts up to about 13 m in thickness (ERAES 1998).

Beneath this aquifer lies the weathered bedrock which extends down tens of metres below the upper aquifer within the drainage valleys.

The deeper aquifer comprises essentially fractured Kombolgie quartz sandstone over most of the area and schists and carbonates of the Cahill Formation further west.

The Magela floodplain sediments consist largely of organic clays and silts with prior stream channels of sand and silt.

4.2.2 Permeability

Seven holes were drilled in the Mine Valley area west of the topographic and groundwater divide (fig 2). These holes were percussion drilled to below the contact between the sandstone

and underlying schist, and then diamond drilled to their respective total depths (AGC-Woodward Clyde 1993). Recorded airlift yields were in the range 5 to 30 kL/day (0.06 L/sec to 0.35 L/sec), although bore T132V recorded 120 kL/day (1.4 L/sec). The main water bearing zones encountered were at the contact between the Cahill Formation schists and Kombolgie sandstone and in the lower sections of the sandstone. The report indicates a transmissivity of 1 m²/day at bore T132V, whilst at Bore V120V the transmissivity is given in the range 0.01 to 0.1 m²/day. Foley (ERAES 1998) has estimated the permeability for the sandstone/schist to be in the range 0.017 to 0.1 m/day in this area.

Drilling in Mine Valley in 1996 also indicated transmissive zones in the shallow carbonates in the Cahill Formation further west, with one bore having a transmissivity of 8 m²/day (hole V081V). Hole U111V also encountered carbonates and was tested at 280 m³/day giving a transmissivity of 5 m²/day, (ERAES 1998). These carbonates lie between the Jabiluka No 1 and No 2 orebody (fig 2). Foley (ERAES 1998) has estimated permeability from these results to be in the range 0.08 to 0.2 m/day in the carbonate/schist.

East of the divide, seven bores drilled to 15 m above the schist and sandstone contact gave only minor water airlift flows. These were too small to be measured accurately (AGC-Woodward Clyde 1993).

From a number of bores constructed east of the divide Foley (ERAES 1998) has reported yields of between 0.5 to 1.5 L/sec from the weathered shallow aquifer between the mine portal and Swift Creek with corresponding permeabilities in the range 10⁻³ m/day to 1.2 m/day. The report indicates permeabilities in the range 3 x 10⁻² m/day to 3 x 10⁻⁴ m/day for the lower sections of the Kombolgie Sandstone in this area.

A 30 m wide pegmatite dyke which crosses the western part of the orebody and dips 80 degrees to the east is referred to in the ERA report (ERAES 1998), but no specific hydraulic testing has been conducted on it. However, the report does indicate that testing in bore U111V demonstrated partial boundary effects in observation bores on the opposite side of the dyke.

4.2.3 Porosity

There is no specific data on porosity on the fractured rocks at the proposed Jabiluka site. However, comparisons can be made with other site areas in the literature with similar rock types to obtain a possible range of values that can be used in this study.

DeWeist (1966) for example indicates porosities in weathered igneous and metamorphic fractured rock of up to 35%, and suggests porosity of non-weathered fractured rock in the range 2% to 10%. Freeze and Cherry (1979) note non-fractured samples of igneous and metamorphic rock have porosities rarely greater than 2%. They quote a fractured weathered or brecciated Yakima basalt having a permeability of 10⁻⁴ to 1 m/day having a porosity of 10%. A tabulated list of porosities in Spitz and Moreno (1996) indicates porosity in fractured dolomite in the range 7% to 18% and fractured granite in the range 2% to 8%.

The quoted values of porosity for sandstone in these references generally have high values at the top end of the ranges. However, at Jabiluka these higher values are probably not relevant except at shallower depths where weathering is extensive. Diamond drill cores inspected at the Jabiluka site showed that at depth there is little weathering and few open fractures. There is no doubt that the large scale jointing evident on the land surface and in the decline under construction will persist at depth. There will also be smaller scale fractures. However, the evidence points to the fractures being tightly closed at depth. For the most part, at depth, the sandstone is highly silicified with virtually no inter-granular porosity or permeability. Overall, the evidence indicates that the sandstone has relatively low bulk porosity and permeability.

In the absence of further data on the Jabiluka sandstone and schist, bulk effective porosities are conservatively estimated to be in the range 0.5% to 5% for fractured rock at depth, and up to 10% for weathered rock.²

4.3 Groundwater quality

Deutscher et al (1980) have described the broad geochemistry of the Jabiluka area. In their investigation during the 1976 and 1978 Dry seasons, 17 exploration holes were drilled in the vicinity of the Jabiluka No 1 and 2 orebodies. These holes penetrated both the Kombolgie Formation sandstone and underlying Cahill Formation schists and were logged for Eh-pH and conductivity at 5 metre intervals to a depth of 195 metres below ground surface. In addition 47 water samples were also collected and analysed from both exploration bores and auger holes constructed on the Magela floodplain and at two nearby billabongs. All samples were reportedly collected 'just below the watertable'. The general location of the groups of boreholes in which water levels and/or water quality have been measured are shown in figure 2. It will be observed that they are in three groups. One is west of the mine site in the Magela floodplain, another is at the orebody, and the third is east of the orebody near the site of the mine's surface facilities in the Swift Creek catchment. Several holes mentioned specifically in the text are marked (eg V081V).

For the 17 exploration holes drilled, analysis indicated that beyond a depth of 5 m from the surface, conductivity was in the range 620 to 680 $\mu\text{S}/\text{cm}$, pH was between 7.1 and 7.6 and Eh was between +60 and +150 mV. The authors of the paper note that there was virtually no variation between each of these parameters in the Kombolgie Sandstone and the underlying Cahill Formation schists.

Of the 47 shallow water samples, those taken above the Jabiluka orebodies 1 and 2 had very low concentrations of chloride, sulphate and silica whilst some samples had higher bicarbonate content. Chloride content was in the range 6 to 20 mg/L, sulphate less than 14 mg/L; silica in the range 5 to 12 mg/L and bicarbonate 50 mg/L to 223 mg/L.

On the floodplain shallow water samples from augured holes (locations shown in fig 2) showed greater ion concentrations. Deutscher et al (1980) summarise the samples characteristics as follows:

- A large proportion of samples contained high concentrations of sulphate (>1000 mg/L).
- High sulphate concentrations (range: 1500 to 6854 mg/L) were usually accompanied by low pH (3 to 4) and a high concentration of Fe^{2+} (200 to 700 mg/L).
- All samples with high sulphate contained higher concentrations of the major ions calcium, magnesium, sodium and potassium.
- No samples had high ion content without a corresponding high sulphate content.

Water samples were also analysed for concentrations of the trace elements uranium, copper, lead, zinc and cadmium. Exploration holes near and above the orebodies had low concentrations of these elements with the highest uranium concentration found to be 0.003 mg/L.

² Effective porosity should be used to calculate the linear groundwater flow velocity rather than drainable porosity (specific yield) which would give an overestimation in travel distance of contaminants. This is so since all of the groundwater in connected fractures or pores (except dead ends) contributes to the movement rather than only that water which is drainable.

In the floodplain, concentrations of uranium were also low with only two samples exceeding 0.01 mg/L. The paper's authors express surprise at these low concentrations since, as noted by them, United States uranium deposits in Colorado have associated groundwater uranium concentrations in excess of 0.1 mg/L, and for a Western Australian example uranium concentrations in the groundwater near uranium deposits are typically in the range 0.02 to 0.08 mg/L.

In general, higher concentrations of the other trace elements were found in the Magela floodplain groundwater (Zn >0.1 mg/L; Pb >0.2 mg/L; Cd and Cu <0.05 mg/L).

Energy Resources of Australia (ERAES 1998) provides groundwater quality results from samples obtained from eight geotechnical boreholes (OB97/1, 2, 3, 4D, 4S, 5, 6 and 7). These holes were constructed east of the divide within a proposed tailings storage area (concept now abandoned) and proposed excavated pit area (concept now shelved). Hole depth ranged from 3.3 metres (OB97/1) to 55.6 metres (OB97/4D). All holes were drilled through the alluvium into weathered sandstone (Kombolgie Formation) except for the 3.3 m bore which was in alluvial sand overlying weathered sandstone. Acidic groundwater with a pH range of 4.5 to 5.0 and low conductivity in the range 17 to 20 $\mu\text{S}/\text{cm}$ was found in the shallow bores OB97/1 and 97/2 (10 m deep). In bores OB97/6 and OB97/4S the pH was in the range 6.6 to 7.3 and conductivity in the range 100 to 200 $\mu\text{S}/\text{cm}$. The deeper bore OB97/4D had a pH of 7.5 and conductivity in the range 300 to 350 $\mu\text{S}/\text{cm}$.

Additional groundwater quality data is available from Kilborn-MWP (1976) for samples collected in 1976, Pancontinental (1981) for samples collected in 1978 and 1979 and ERA for samples collected in 1992, 1993, 1996 in the Mine Valley area. All data are listed in ERAES (1998) tables 3 to 8. These tables are consistent with concentrations reported in the previous findings. The additional information given for the period 1992/96 includes manganese concentrations that were found to be in the range 0.03 to 3.5 mg/L with an average of around 0.3 to 0.4 mg/L. Also uranium concentrations are reported to be in the range 0.2 $\mu\text{g}/\text{L}$ (Bore V081V) to 132 $\mu\text{g}/\text{L}$ (Bore T132V) and radium 226 in the range <2 mBq/L (Bore W135V) to 1078 mBq/L (Bore T132V). Both these bores are within the boundary of the orebody No 2 whilst Bore V081V lies outside of the orebody.

In summary, measured values of groundwater quality at Jabiluka can be separated into two distinct groups. The first group includes groundwater within the fractured bedrock and overlying weathered zone beneath and immediately adjacent to the ridge and extending to Swift Creek in the east. 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 ionic content, high sulphate and iron and low pH. Overall, concentrations of naturally occurring radionuclides are low.

It is considered that chemical characteristics of the first group can be largely attributed to flushing action through high levels of Wet season recharge along the topographic ridge and the relatively inert sandstone.

For the second group, the chemical characteristics are largely due to decay of organic matter and oxidation of pyrite and seasonal floodwater fluctuations along the floodplain creating alternating reducing and oxidising conditions. It should be noted that acid sulphate soils occur extensively in the floodplain. Their significance is discussed by East et al (1992).

The occurrence of low concentrations of radionuclides in groundwater at this site compared to other sites elsewhere in Australia and the US is probably also due to Wet season groundwater dilution which is high compared with that which would occur in arid climates at these other sites.

4.4 Groundwater – flow directions and dynamics

4.4.1 Recharge and potentiometric surface

Recharge of the groundwater system is through direct infiltration of rainfall and through infiltration from local natural depression storages filled by runoff from the ridge. Both shallow and deeper groundwater originates from the overlying shallow aquifers with percolation of groundwater into the weathered zone and then preferentially along higher permeability zones into the deeper fractured rock aquifer. Because of the lower permeability of the underlying weathered zone and fractured bedrock, vertical flow is somewhat impeded, with predominant flow in a horizontal direction along the more permeable shallow aquifer. Nevertheless, the similar low salinity groundwater found in the fractured bedrock would suggest continual flushing with water recharged during annual Wet seasons.

Bore water levels (ERAES 1998) show that groundwater flows to the east and west away from the Jabiluka Mine Valley topographic ridge. On the western side of the ridge groundwater flows west towards the Magela floodplain, whilst to the east it flows towards Swift Creek. Potentiometric heads in the deeper aquifer in the vicinity of the divide are reported to be lower than those in the shallow aquifer, indicating a downward component in the hydraulic gradient in this area (ERAES 1998).

Based on accepted hydrogeological principles, groundwater flowing to the west would have the potential to join groundwater flowing in a northerly direction beneath the Magela floodplain, whilst groundwater flowing to the east would tend to flow in a northerly direction once it reaches the Swift Creek catchment (fig 1, 2). Milnes et al (1998) support this conceptual model of the flow system.

5 Proposed tailings repositories

5.1 Previous proposals

The initial proposal for storing tailings involved construction of an above ground tailings storage to the east of the divide. Subsequently two sub-surface disposal pits, respectively 100 m and 180 m deep, were proposed to take excess tailings material that could not be accommodated within the mine voids. However, Waite et al (1998) expressed reservations about the suitability of the site for the pits.

ERA have now proposed the construction of sub-surface tailings silo storages to meet the current approval condition that all tailings must be stored in underground repositories.

5.2 Proposed silo storage bank

The proposed silo bank area is shown outlined in figures 2 and 3. About 180 vertical silos, 20 m in diameter are to be spaced at 30 m centres and extend from RL 955 m mine level down to about RL 820 m. Each silo is to be filled with a tailings paste prepared from partially de-watered tailings and cement.

5.3 Mine void storage

The primary tailings repository will be the excavated stopes in the mining zone of Jabiluka orebody No 2. Longhole open stoping mining is usually carried out with alternate removal of rectangular stopes in a checkerboard pattern. The mining sequence would probably include filling each alternate stope prior to the removal of each adjacent stope.

6 Tailings characteristics

6.1 Comparison with Ranger Mine tailings

Although tailings have yet to be produced at Jabiluka, it is expected that when they are they will be similar to those produced at the nearby Ranger mine. The host rock for the uranium in both cases is Cahill formation schist which can be expected to mill in a similar manner at the two processing plants. Laboratory and field testing by the CSIRO (Richards et al 1989) of the properties of tailings in the Ranger tailings pond yielded extensive data on physical and chemical properties.

The Ranger tailings were not deposited as a paste. However, the measured permeabilities can be taken as a guide to those likely to apply to uncemented Jabiluka tailings. Appropriate testing to determine an optimal paste mix should allow a permeability lower than that of uncemented tailings to be achieved. Pore water chemistry will be affected by the addition of cement. Again, appropriate paste mix design should prevent contaminants being leached as easily from the set paste as it would be from uncemented tailings.

Paste and pore water properties assumed in the analysis during this investigation take into account the measured properties of the Ranger tailings.

6.2 Proposed paste disposal and properties

As noted above, the current proposal is to dispose of the mill tailings at Jabiluka as a paste material in underground repositories.

The paste material will comprise a dense, low permeability, viscous mixture of tailings and water having the consistency of 'wet cement', with low segregation properties (Cincilla et al 1997). It is common to add a percentage (3 to 6%) of cement to bind the tailings into a solid mass, thereby improving the strength and reducing the permeability. A cement content of 1% to 4% is envisaged by ERA in this case. A review of the technology has been prepared recently by Waite et al (1998), although this is currently being reassessed as part of a research project.

Although the paste material would be of low permeability there is currently no specific data available on the probable range of magnitude of the permeability of the cured tailings paste. Waite et al (1998) have indicated uncertainty of the magnitude of permeability reduction which could be accomplished by the addition of cement to the paste if it is placed under water.

It has been suggested (Kinhill & ERAES 1998 – page 4-38 of Jabiluka Mill Alternative, Public Environment Report) that the permeability of a non-cured paste (no added cement) may be at least half an order of magnitude (ie 5 times) lower than that of conventionally deposited tailings. Tailings normally have a permeability in the range 10^{-2} m/day to 10^{-3} m/day (about 10^{-7} m/sec to about 10^{-8} m/sec) if the effects of overburden pressure are not included (Richards et al 1989). The permeability of a paste without added cement could be expected to be somewhat lower than this range.

It is noted in the Jabiluka EIS that adding 4% cement to the paste decreases the permeability from 10^{-7} m/sec to 10^{-10} m/sec (ie from about 10^{-2} m/day to about 10^{-5} m/day). However, it is not known from where these values were obtained or derived.

Given that saturated permeability of the host sandstone rock is generally in the range 10^{-2} to 10^{-4} m/day it is possible that the permeability of the paste could therefore be up to two orders of magnitude less than the average permeability of the host bedrock.

Both Milnes et al (1998) and Waite et al (1998) note that there is no quantitative data available on the leaching characteristics of uranium tailings pastes under buried saturated conditions. In particular, the mass flux rates and adsorption behaviour of specific contaminants from this material in contact with flowing groundwater are unknown. Conservative estimates have been used in the modelling. ERA is currently investigating tailings paste properties. This will allow the modelling to be refined in the future.

The absence of specific permeability data and leaching characteristics of the paste material has been highlighted by both Milnes et al (1998) and Waite et al (1998).

The possibility of acid occurrence/formation within the paste because of sulphate in the process water and the sulphide content of the tailings has been reviewed. It has been concluded that sulphate acidity will be neutralised by the cement content of the paste material if sufficient cement is added (DLPE 1998). However, tests to examine the setting properties of the paste and its long-term chemical stability are considered essential to verification of permeability assumptions made in the analysis of groundwater flow and dispersion of contaminants described in this report.

6.3 Potential contaminants

Potential contaminants to be addressed in this report are magnesium sulphate, manganese, uranium and radium (specifically radium 226).

6.3.1 Magnesium sulphate

This compound is one of the main contaminants to be contained in the tailings waste material. Waite et al (1998) have indicated up to 50 000 mg/L of sulphate in the process water at Ranger, and tailings water with typical concentration of 20 000 mg/L sulphate. It is not known at present what the concentration might be in either the silo or mine fill paste or the adsorption characteristics, if any, of this chemical within this material. In general, it would be expected that both sulphate and magnesium would have low adsorption characteristics.

6.3.2 Manganese

The Ranger process water contains 2440 mg/L of manganese but the tailings pore water generally contains less than 1000 mg/L. Similarly high levels could be expected in the Jabiluka process water but, after neutralisation and processing tailings to form a paste, the concentration of manganese in Jabiluka tailings pore water is unlikely to exceed 500 mg/L. Adsorption of manganese is known to occur. However, it is complicated by redox reactions that affect aqueous species and transformations, and the formation of manganese compounds of different oxidation states (EPRI 1984). It would be expected that manganese would have moderately high adsorption characteristics in the aquifer. No data are available on the adsorption characteristics of manganese in the tailings paste material.

6.3.3 Uranium

Uranium concentrations in the Ranger tailings water had a concentration of 500–1000 µg/L up to 1988 (AGC 1989). ERA has quoted (pers comm) 1 mg/L or 10 Bq/L for the Ranger

tailings pore water. For the richer Jabiluka ore, the concentrations in tailings could be expected to be about 50% higher. No data are currently available about the adsorption characteristics of uranium within the paste material.

6.3.4 Radium 226

Radium 226 is one of the decay products of uranium 238 having the longest half-life (1600 years) of all the radium isotopes. The decay of radium 226 in turn results in radon (Rn 222), an inert gas that has a half-life of 3.82 days and can be carried by groundwater.

Radium 226 is also known to be capable of being transported by groundwater and its mobility has been extensively studied near the Jabiluka project area at the Ranger uranium tailings storage (Martin & Akber 1996). This study reported a five-fold increase from 50 mBq/L to 250 mBq/L in radium 226 concentration over a period of ten years in one bore (OB11A) located approximately 150 m to 200 m down-gradient from edge of the stored tailings. In a second bore (OB13A) at about the same distance, a two-fold increase was noted during the available record, although concentrations fluctuated and subsequently decreased to 1983 values in 1993. Other bores (OB 16, OB 15) either showed no increase in water levels, or fluctuating water levels with no overall increase in levels. During the 1983 to 1993 period the radium 226 concentration in the tailings varied from 30 000 mBq/L to 20 000 mBq/L respectively.

Using detailed radium isotope ratio analysis Martin and Akber (1996) concluded that the variation in radium 226 concentration down gradient in the observation bores were due to two processes:

- Desorption of available radium from adsorption sites caused by the increase in other cations (eg Mg and Ca) in solution, the increase in radium being a contribution from the aquifer and not due to transport from the tailings dam.
- Formation of a barite phase with co-precipitation of radium.

That is, the fluctuations were not due to radium transport processes, which, although present, were being masked by the geochemical adsorption/desorption.

No data are currently available on the adsorption characteristics or concentrations of radium 226 in the tailings.

6.4 Mobilisation of potential contaminants

6.4.1 Leaching potential – silo bank

Under buried conditions and with cured paste permeability likely to be similar to or lower than the fracture permeability of a large portion of the host rock, groundwater will preferentially flow around the silos. Even if the bulk permeability values are similar, each cylinder of paste will block off fractures acting as preferential groundwater flow paths and much of the water will be diverted around the cylinder. The length(s) of the diversion path(s) and the consequent increase in head loss and reduction of flow through the silo bank as a whole will depend on connections within the fracture network. If the permeability of the paste is less than the bulk permeability of the surrounding rock the effect will be correspondingly greater. Under both conditions the mass flux of contaminants emanating from the silos would be much lower than if the groundwater flowed directly through the matrix of the silo tailings. The permeability of the paste and the adsorption characteristics of the contaminant in the paste and the surrounding fractured rock would control concentrations within the flowing groundwater. Specifically, the adsorption characteristics of the contaminant in the tailings

paste will determine the paste pore water concentrations and the permeability of this material will control the rate of leaching.

Lowering the permeability of the tailings paste will decrease proportionally the leaching rate of the resulting tailings paste pore water. In this report the effect of both adsorption and paste permeability in a single and group of silos is examined using a numerical flow and solute transport model. This work is described in detail in Appendix B.

6.4.2 Leaching potential – mine void fill

The comments made regarding the adsorption and leaching characteristics of the silos also apply to the mine void tailings. However, there are probably some differences regarding the uniformity of the placement of the mine void tailings compared to those in the silos where placement conditions can be better controlled. This could result in voids or fissures which would allow greater groundwater throughflow. Also the structural integrity of the paste material in the filled stope(s) after curing is less certain than that of paste in the cylinders. The fill in the stopes will be used for structural support and rock movement could cause cracking or more serious failures.

Whether any fissures are likely to develop during blasting/excavation of adjacent stope(s) or as a consequence of longer-term ground movements will depend on the strength and plasticity of the set paste. Any cracks that do develop will allow a greater level of throughflow. Conversely, the higher cement content of the paste in the stopes will act to reduce the hydraulic conductivity of the matrix.

7 Analysis of contaminant movement

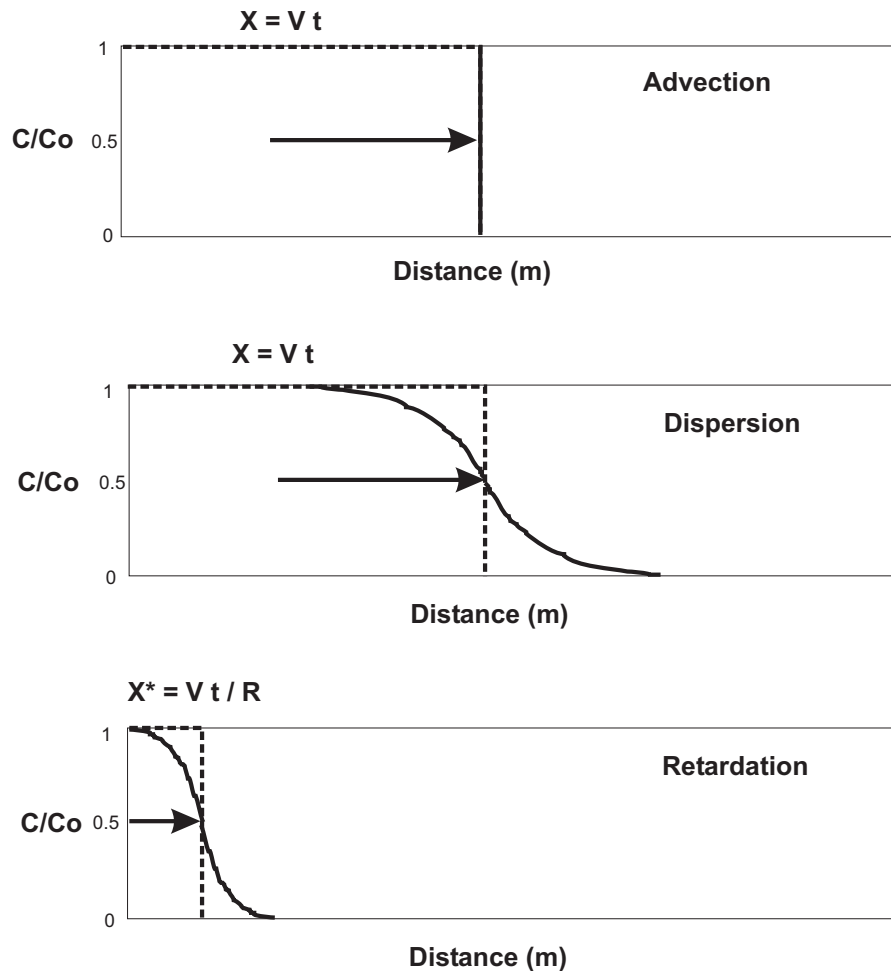
7.1 General principles

7.1.1 Advection-dispersion-retardation

Essentially three processes control the movement of a contaminant in the sub-surface. The first of these is advection that potentially moves or transports the contaminant with the velocity of the surrounding groundwater in a sharp concentration front (fig 4). Advection is the Darcy velocity divided by the effective porosity and therefore is larger than the Darcy velocity. As the effective porosity³ decreases, the advective velocity increases for a given Darcy velocity and vice versa. Advective velocity is usually referred to as linear or pore velocity.

Dispersion, on the other hand, can spread the contaminant in three different co-ordinate directions due to variations in groundwater velocity caused by local permeability differences within the sub-surface strata or rock mass. The parameter describing the degree to which the contaminant will spread in any of the three primary directions is dispersivity, which has the dimension metres. Higher values of dispersivity will cause greater spreading and consequently lower concentrations with increasing distance from the source and vice versa.

³ Effective porosity is smaller than (total) porosity as it excludes dead end pores or structures that are not connected. Effective porosity is larger than drainable porosity (ie specific yield) and much larger than storage co-efficient.



V = Linear Velocity
t = time
X = Travel Distance
R = Retardation
C = Concentration at distance
C₀ = Source Concentration

FIGURE 4
 Jabiluka Review
 Groundwater Hydrology
 Advection-Dispersion
 -Retardation

Figure 4 Advection-Dispersion-Retardation

Retardation is a broad term encompassing adsorption, precipitation/dissolution and other complex ion exchange reactions. In its most fundamental sense it can have the effect of retarding or slowing the velocity of the contaminant relative to the flowing groundwater. It is generally recognised that the concept of retardation is a simplification, but it is often necessary to invoke it given the limited hydrochemical data and uncertainty about the chemical reactions and conditions that may occur in the sub-surface. Despite this, it has been shown to describe quite well contaminant plume movement at sites subjected to very detailed monitoring. Use of this concept greatly simplifies the contaminant modelling process.

Adsorption is commonly viewed as the process where contaminant adheres to the surface of the porous medium or rock mass due to a number of different mechanisms. Adsorption is usually quantified by a measure of the amount of contaminant mass held by the rock or porous medium compared with the contaminant mass in the flowing groundwater. The relationship between the amount of a solute held by the rock and that remaining in solution in the groundwater is called an isotherm.

Distribution co-efficient K_d

The simplest isotherm⁴ is the distribution co-efficient where the contaminant mass on the rock or porous matrix is given by:

$$S_m = K_d C \quad (1)$$

where K_d is the distribution coefficient [L^3/M]; S_m is the mass of the contaminant adsorbed or precipitated on the solids of the matrix per unit bulk dry mass of the media [M/M] and C is the contaminant concentration [M/L^3].

In fractured rocks K_d is better defined as K_a [L] which is the mass of contaminant on the rock surface per unit area of the rock divided by the contaminant concentration within a fracture (Freeze & Cherry 1979).

An important assumption made in the derivation of equation (1) is that there is infinite capacity of the media to adsorb the contaminant. This assumption is reasonable for low concentrations.

Equation (1) is the equation most often used in solute transport simulations. It is a linear relationship and is the only relationship that can be included in commonly available analytical models.

Freundlich isotherm

This non-linear isotherm allows for decreases in the capacity to adsorb contaminant as the concentration increases and is given by (EPRI 1984):

$$S_m = K_f C^{1/N} \quad (2)$$

where K_f and N are constants. When $N=1$ then K_f is the same as the distribution co-efficient constant K_d above.

Langmuir isotherm

This isotherm limits the adsorption to a maximum value as concentration increases and is given by (EPRI 1984):

$$S_m = K_L A_m C / (1 + K_L C) \quad (3)$$

where K_L is the Langmuir adsorption constant and A_m is the maximum adsorption capacity of the matrix.

Whilst non-linear isotherms can be incorporated into the numerical models used in this study, their use could not be justified in this case because of the limited data available.

Retardation factor

Using equation (1) to describe the retardation process, the retardation factor R_f can be expressed as:

$$R_f = 1 + \rho_b K_d / n \quad (4)$$

where ρ_b is the bulk density of the aquifer and n is the effective porosity.

The contaminant velocity is therefore given by $v_c = v_L / R_f$ where v_c is the contaminant velocity and v_L the linear (pore) velocity and $v_L = v_D / n$ where v_D is the Darcy velocity.

In a uniform fracture the retardation factor is given by $R_f = 1 + AK_d$ where A is the surface area to void space (volume) ratio [$1/L$] (Freeze & Cherry 1979). For a planar fracture $A = 2/b$ where b is the aperture width.

⁴ Not strictly an isotherm but a constant.

7.1.2 Radioactive decay

Radioactive decay is given by the decay constant:

$$\lambda = \text{Ln}(2) / t_{1/2} \quad (5)$$

where $t_{1/2}$ is the half life [T].

7.1.3 Dilution

Dilution normally refers to reduction of concentration by mixing of water containing a substance (eg a contaminant) with water of lower concentration entering the flow system from another source. In this respect it differs from dispersion in that dispersion is caused by velocity variations in the aquifer alone and simply distributes the contaminant more widely throughout the system.

In the Jabiluka mine area, dilution would involve mixing of deep groundwater carrying contaminants leached from the stored tailings with groundwater of more recent origin. This recently recharged water has travelled only through the relatively inert surface layer of soil and rock and is thus less contaminated than the deeper flowing water.

8 Modelling approach

8.1 General

Groundwater flow and contaminant transport are complex three dimensional processes. Metalliferous mining usually involves fractured rock aquifers with the fractures providing the main flow paths for the groundwater which has the potential to transport contaminants away from the mine area. The scale of the fracture network is usually small compared with that of the region of interest in potential contamination so a fractured rock aquifer can be represented as an equivalent porous medium on a regional scale. Only exceptional geological features such as major faults need to be accounted for separately as flow conduits.

Geological conditions at Jabiluka meet the above modelling scale criterion. However, the data available to describe the hydraulic characteristics of the aquifer do not justify a fully three dimensional model to represent flow and contaminant transport. In most cases of mining the available data are less than desirable. In this case ERA has particular difficulties to overcome because of restrictions on access to areas from which data are required.

Data are available to allow modelling of flow along the main flow paths and potential contaminant transport routes east and west from the mine towards the Magela floodplain in Kakadu National Park. Consequently, modelling has been carried out to first determine flow velocities in these directions and then to estimate the transport of contaminants from tailings repositories to and along these paths. The overall model can be described as hybrid. Details are given below and in Appendices A and B.

8.2 The hybrid model

As indicated in the previous section, a hybrid modelling approach has been used in this investigation. The models used include:

1. A two dimensional (2D) section finite element model (SEEP/W) of section A-B-C to determine flow directions, head distributions and the range of Darcy velocities along a section parallel to the groundwater flow lines extending west then north and east then north of the Mine Valley topographic divide (figure 1 – section A-B-C).

2. A three dimensional (3D) numerical solute transport model (MODFLOW-SURFACT) applied to a single representative 1 metre thick horizontal layer of flow through and around a repository to determine the leaching concentrations from the tailings paste material for use as the source concentrations in the analytical model (an analysis of this work is described in Appendix B).
3. An analytical contaminant transport model (Appendix A) to determine concentrations due to advection, dispersion in three co-ordinate directions and retardation. This model uses as input the range of velocities determined from 1 above and source concentrations determined from 2 above. This model has been combined with Monte Carlo simulations to determine concentration profiles for a large number of different parameter values within selected ranges.

The models have been chosen to provide levels of approximation which match that of the available data. The numerical solute transport leaching model and the numerical flow model provide data of appropriate accuracy to be entered into the analytical contaminant transport model.

Calculations of contaminant concentrations that may emanate from the tailings paste and the concentrations within the aquifer system have been expressed in relative or normalised form. Relative or normalised concentrations are fractions or percentages of the source concentrations whatever they may happen to be. The results in this report can therefore be used to determine absolute concentrations at downstream points for a range of source concentrations. Absolute concentration values that are based on Ranger mine data and the literature, and considered to be conservative, are given in section 13.1. These may be used to assess the impact of the tailings repositories on water quality in the Mine Valley and Swift Creek areas.

8.3 Contaminant characteristics

8.3.1 Magnesium sulphate

In general sulphate is weakly retained on soils and most adsorption is associated with hydrated Al and Fe oxides (EPRI 1984). EPRI provides tables of values of Langmuir A_m and K_L and Freundlich K_f and $1/N$ isotherm constants; however, these are for materials and soils that are not directly relevant to the current site. Nevertheless, they indicate low adsorption for various soils with K_f in the range 0.006 to 0.127 and $1/N$ in the range 0.48 to 0.77. For some of the same soil types the reference gives A_m in the range 2.7 to 4.1 and K_L in the range 3.2 to 3.9.

EPRI indicate that sulphate adsorption increases somewhat at lower pH.

As a conservative estimate sulphate is treated as a non-reactive (ie no adsorption) contaminant in the solute transport analysis, that is it is assumed that $K_d = 0$.

8.3.2 Manganese

EPRI (1984) provide adsorption isotherm constants for manganese for various adsorbents and pH. These constants are not representative of the actual site conditions. For sand loam the values of A_m are 8.0 and 8.7 and corresponding values for K_L are 3.5 and 4.0. for pH of 5.2 and 6.7 respectively.

In the Ranger tailings dam concentrations of manganese in pore water have been measured as 140 mg/L near the bottom of the deposited tailings and 900 mg/L near the top and in the supernatant liquid.

For Ranger uranium tailings solute transport modelling, a K_d value of 1.5 was used to match model and measured results (AGC 1989).

8.3.3 Uranium

Moody (1982) presents empirically derived distribution coefficient K_d values from batch experiments for selected radionuclides. Relevant values from these tables are shown in table 1. (See also Domenico and Schwartz 1990.)

Table 1 K_d distribution co-efficient (mL/g) values from batch experiments (Moody 1982)

Element	Host environment			
	Salt	Basalt	Tuff	Granite
Uranium	1*	6*	4*	4*
Radium	5	50	200	50
Thorium [§]	50:1002**	500	500	500

* No significant difference between values measured in oxidizing and reducing Eh.

** First value for dome salt, second for bedded salt.

§ Although not included in the list of elements for this brief thorium has a K_d value and therefore a retardation at least one order of magnitude (ie x 10) larger than radium 226 according to table 1

The table indicates that salinity, in particular high salinity, has a marked effect on reducing the K_d values and therefore the retardation factor. For uranium it reduces the K_d by a factor between 4 to 6 and radium by an order of magnitude or more.

Based on equation 4 the corresponding retardation factors for the sandstone and schists at Jabiluka using an average mass density of 2.0 g/cm³, porosity in the range 2 to 10% and K_d in the range 1 to 6 mL/g are given in table 2.

Table 2 Range of estimated retardation factors for uranium in the Kombolgie and Cahill formations

K_d (mL/g)	Retardation factor for porosity 2%	Retardation factor for porosity 10%
1	100	20
6	600	120

8.3.4 Radium 226

Table 1 above provides estimates of K_d values for radium 226. Table 3 gives the corresponding calculated retardation factors.

Table 3 Range of estimated retardation factors for radium 226 in the Kombolgie and Cahill formations

K_d (mL/g)	Retardation factor for porosity 2%	Retardation factor for porosity 10%
5	500	100
50	5000	1000

Note that in the above tables 2% has been used as the lowest effective porosity for comparison since lower values than this would give larger values of retardation factor. In this analysis we require conservative lower values of this factor.