Assessment of the Jabiluka Project

Report of the Supervising Scientist

to the

World Heritage Committee

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Preface

For almost twenty years, the mining and milling of uranium has been undertaken by Energy Resources of Australia at the Ranger mine in Australia's Northern Territory. The Ranger Project Area has become surrounded by, but has never formed part of, Kakadu National Park which is inscribed on the World Heritage List. Further international recognition is granted Kakadu National Park, as its wetlands are listed under the Convention on Wetlands of International Importance. Because of the significance attached to Kakadu National Park by the Australian and the international community, the Commonwealth Government established a unique regime for environmental protection in the region, which demands that the highest level of environmental protection be achieved.

Following the Government's approval for the establishment of a second uranium mine on the Jabiluka Mineral Lease which, like the Ranger Project Area, is excised from, but surrounded by Kakadu National Park, the Bureau of the World Heritage Committee sent a Mission to Kakadu to establish whether or not the World Heritage values of Kakadu were under threat from the Jabiluka project. The Mission concluded that both the natural and the cultural values of Kakadu are seriously threatened by the development of the Jabiluka mine and recommended that Kakadu be placed on the List of World Heritage Sites in Danger.

After discussion of the Mission's report at its meeting at Kyoto from 30 November 1998 to 5 December 1998, the Committee requested that the Supervising Scientist conduct a full review of scientific issues raised by the Mission. Perceived scientific uncertainty with respect to these issues had led to the Mission's conclusion that the natural values of Kakadu are threatened by the Jabiluka project. This report is in response to that request.

It must be emphasised that this report does not purport to be a complete environmental impact assessment of the Jabiluka project. There are many environmental protection issues related to the development of Jabiluka that were not raised in the Mission's report or in the decision of the World Heritage Committee. These broader issues have already been addressed in the environmental impact assessment process to which the Jabiluka project was subjected and are covered by the requirements that the Commonwealth Government imposed in granting its approval for the project to proceed.

This report includes a thorough review of all of the issues raised by the World Heritage Committee and provides a detailed assessment of the risks to the wetlands of Kakadu arising from the storage of uranium ore at the surface at Jabiluka, the management of water and the storage of tailings. The conclusion of this review is that, contrary to the views expressed by the Mission, the natural values of Kakadu National Park are not threatened by the development of the Jabiluka uranium mine and the degree of scientific certainty that applies to this assessment is very high.

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Supervising Scientist
9 April 1999

Acknowledgements

1 Executive summary

1.1 Introduction

At the twenty-second meeting of the World Heritage Committee, held in Paris from 22 to 27 June 1998, a decision was reached that the Chair of the Committee should lead a mission to Australia and Kakadu National Park to assess any ascertained or potential threats to the World Heritage values of Kakadu National Park that might arise from the proposal to mine uranium at Jabiluka. The visit of the Mission took place from 26 October 1998 to 1 November 1998.

The report of the Mission was submitted to the Bureau of the World Heritage Committee at its meeting held in Kyoto, Japan, on 27–28 November 1998. Following consideration of the report, the Bureau made recommendations that were considered by the World Heritage Committee at its meeting from 30 November 1998 to 5 December 1998.

The report noted 'severe ascertained and potential dangers to the cultural and natural values of Kakadu National Park posed primarily by the proposal for uranium mining and milling at Jabiluka' and recommended that the mining and milling of uranium should not proceed. In the case of threats to the natural values of the Park, the mission placed very significant weight on 'the serious concerns expressed by some of Australia's most eminent scientists as to the degree of scientific uncertainties relating to the Jabiluka mine design, tailings disposal and possible impact on catchment processes'. The concerns cited were made in a submission by Wasson, White, Mackey and Fleming (Wasson et al 1998, Appendix 2).

Because the Australian authorities had not had sufficient time to respond to the report, the World Heritage Committee made no firm decision of the future status of Kakadu at the November 1998 meeting. In its decision, the Committee requested that the Supervising Scientist conduct a full review of the areas of scientific uncertainty. The issues specified were hydrological modelling, prediction and impact of severe weather events, storage of uranium ore on the surface and the long-term storage of mine tailings.

This report is the Supervising Scientist's response to that request. In preparing this report, the Supervising Scientist has drawn on the broad range of expertise available within his own organisation. In addition, given the intense interest in the World Heritage issue and the need for absolute transparency, he has sought independent expert advice from a number of scientific institutes within Australia. Scientists from the the Bureau of Meteorology, the University of Melbourne, the Commonwealth Scientific and Industrial Research Organisation and the University of New South Wales prepared reports on specific topics at the request of the Supervising Scientist. These reports are included as attachments to this report.

1.2 Issues to be addressed

Following a detailed examination of the submission by Wasson et al (1998) and the Mission report, the Supervising Scientist has summarised the main issues arising under each of the topics specified by the World Heritage Committee and confirmed this interpretation with the Chair of the Committee. This summary is as follows:

Hydrological modelling

> This topic includes issues raised by Wasson et al (1998) in section 5 of their submission; in particular, (i) the estimate of what constitutes a 1 in 10,000 AEP annual rainfall for the

purpose of designing the retention pond, (ii) evaporation in the exit air stream of the mine ventilation system and (iii) evaporation from open water.

Prediction and impact of severe weather events

This topic refers to (i) uncertainties raised by Wasson et al (1998) in section 4 of their submission arising from the work of Nott (1996) about high discharges in the Waterfall Creek region and the Katherine floods, (ii) uncertainties expressed by Wasson et al (1998) on what constitutes a Probable Maximum Precipitation (PMP) event and (iii) the effect of climate change on both mean annual rainfall and the intensity of storms.

Storage of uranium on the surface

Included under this topic are (i) the design of the surface facilities to ensure, taking into account issues raised in the first two topics above, that runoff from the ore stockpile will all be collected by the retention pond even under extreme weather conditions and (ii) the adequacy of parameters used in the design of the retention pond to ensure containment of water collected in it under extreme weather conditions without the need to release water to the surface water system beyond the mine site.

Long-term storage of the mine tailings

This topic includes two issues related to the long term containment of 100% of the tailings at Jabiluka in the mine stopes and additional stopes/silos excavated near the ore body specifically to contain tailings. The two issues are (i) long-term containment of the solid tailings so that they do not represent a threat to the wetlands of Kakadu and (ii) dispersal of contaminants in groundwater from the contained tailings and their consequent potential impact on the wetlands of Kakadu.

There are a number of additional issues raised in the submission by Wasson et al (1998) that require clarification. These and other more general issues are also addressed in this report.

1.3 Summary of findings

Hydrological modelling issues

The conclusions and recommendations of the Supervising Scientist on the hydrological modelling issues raised by Wasson et al (1998) are as follows.

Estimate of the 1:10,000 AEP annual rainfall

- It is recommended that the Oenpelli rainfall record for the years 1917 to 1998 should be used for estimating the 1:10,000 AEP annual rainfall and for other hydrological modelling for the Jabiluka project because it is much more extensive than that at Jabiru and is consistent with the Jabiru record in the period of overlap.

- The recommended value for the 1:10,000 AEP annual rainfall is 2460 mm with 95% confidence limits of ±190 mm. This estimate is in very good agreement with the value adopted by ERA, 2450 mm.

- It is acknowledged that there may be some residual model dependence in the recommended value for the 1:10,000 AEP annual rainfall. However, this is not important for modelling of the Jabiluka water management system in this review because a Monte Carlo simulation method is used based upon stochastically generated rainfall data.

Evaporation from open water

- All of the suggestions made by Wasson et al (1998) to check the validity of the evaporation pan factors used by ERA had already been taken into account in the

evaporation calculations presented by ERA in its hydrological modelling of the water management system for the Jabiluka project.

- Based upon two recent independent reviews, it is recommended that, in all future hydrological modelling of the Jabiluka water management system, the pan factors proposed by the Supervising Scientist in 1987 be used.

- The difference in annual pond evaporation arising from the use of the pan factors recommended by the Supervising Scientist compared to that obtained using the factors adopted by ERA in the Public Environment Report for Jabiluka is small (about 2%). This difference is well within current expectations of the accuracy of water management modelling.

- The volume of the retention pond at Jabiluka would need to be increased by about 3% to take into account the interannual variability in evaporation and the inverse relationship between evaporation and rainfall.

- This estimate is, however, considered to be an overestimate because the relationship between evaporation and rainfall is not linear. Rather, evaporation during the main months of the Wet season tends towards a constant value at high rainfall.

- It is recommended that a linear relationship between evaporation and rainfall is incorporated in future water management modelling because this will yield conservative results under high rainfall conditions and more realistic results under drought conditions than would be obtained using the long-term monthly average evaporation.

Evaporation in the mine ventilation shafts
- The observation by Wasson et al (1998) that the latent heat of evaporation needs to be supplied is correct. The conclusion that this results in a major error is, however, invalid because the energy required can be supplied externally, and it was the intention of the design engineer that the optimum way of doing this would be assessed at the detailed design stage once approval for the project to proceed had been given.

- The capital and operating costs of a humidifier system designed to meet the evaporation energy needs would be high and a cost benefit analysis of various water management options will be required before a final decision on the installation of a humidifier system is made.

- If it is decided that the cost of installing and running a humidifier system is too high or that the environmental impact is unacceptable, the retention pond at Jabiluka would need to be increased in area from 9 ha to about 13 ha. Given the experience of the Ranger Mine, which has a disturbed area of about 500 ha, this 4 ha increase is not expected to give rise to any detectable environmental impact.

Prediction and impact of severe weather events
Evidence on past severe weather events in the region
- The assumption of Wasson et al (1998) on need to design and build tailings and water retention dams that will be structurally stable for 10,000 years and will totally contain all water that might accumulate over this period is incorrect.

- The project approved by the Minister for the Environment required all tailings to be returned underground to the mine void and to additional stopes or silos specially excavated to contain the tailings. There will, therefore, be no need to contain tailings in surface repositories for any period longer than the mine life, approximately 30 years.

Similarly, water retention structures will be evaporated to dryness and rehabilitated at the cessation of mining.

- The strongly worded criticism in Wasson et al (1998) that the proponent has assumed stationarity of climate over a period of 10,000 years is, therefore, without foundation. Citing this and information on significantly different climate regimes in the region in the past few thousand years as evidence that 'the integrity of Kakadu cannot be guaranteed with any probability' is unjustified.

Probable maximum precipitation events

- The 6-minute PMP intensity estimate adopted by ERA for the Jabiluka project is approximately 20% lower than the value recommended by the Bureau of Meteorology. It is recommended that the Bureau value be used in the detailed design of the Jabiluka project.

- A full set of PMP values appropriate for Jabiluka is provided in this report. It is recommended that these values be used, where appropriate, in the detailed design of the Jabiluka project.

Effect of climate change on hydrological modelling

- As recommended previously by the Supervising Scientist, it is important that possible or likely variations in climate over the next 30 years are properly taken into account in the detailed design of the water management system at Jabiluka. This should include non-greenhouse effects such as periodic changes in the mean annual rainfall that occur in the past meteorological record.

- There is substantial agreement in the predictions of the various climate change models on the projected temperature increase in the region of Jabiluka by the year 2030. The increase is expected to be in the range 0.35–0.8ºC.

- There is substantial agreement in the predictions of the various climate change models, including models that incorporate regional climate modelling, on the likely change in the Wet season rainfall in the region of Jabiluka. The predictions range from +1% to -6% by 2030. These models confirm previous expectations that any increase in Wet season average rainfall due to global warming is likely to be small (1%).

- Decadal scale variation is the most significant climate change effect for hydrological modelling of the Jabiluka project. The present review confirms the earlier analysis of the Supervising Scientist that this effect could be as large as 15% over the next 30 years. However, this review has established that stochastic rainfall series modelling, based upon the Oenpelli rainfall record, fully accounts for decadal scale variability and that there is no need to include this effect explicitly in a climate change scenario.

- Analysis of the historical rainfall record at Oenpelli reveals an upward trend of 1.7 mm per annum in the mean annual rainfall that may be attributed to global warming and which should be added to the model predictions. The observed trend is not statistically significant but the adoption of a precautionary approach implies that the significance of this possible trend should be assessed in hydrological modelling of the Jabiluka project. However, stochastic rainfall series modelling, based upon the Oenpelli rainfall record, also exhibits a similar trend and it is concluded that there is no need to include this effect explicitly in a climate change scenario.

- As in previous studies, this review has found that the intensity of extreme storm events is likely to increase despite the fact that there is an overall decrease in the annual rainfall.

- Climate change modelling also suggests that there could be a significant increase in the magnitude of PMP events, with increases of up to 30% being suggested. Possible increases of this magnitude should be taken into account in the final design of the Jabiluka water management system by increasing the height of exclusion bunds. This is an action that can be incorporated at the detailed design stage.

The storage of uranium on the surface

Modelling of the water management system at Jabiluka under current climatic conditions

- This review has included hydrological modelling of the water management system at Jabiluka using a stochastic daily water balance model which incorporates the recommendations of this review on the appropriate rainfall record and evaporation, a realistic distribution of evaporative losses in the ventilation system throughout the year, and a simple soil water capacity model for runoff. The system modelled was the Jabiluka Mill Alternative – Original Concept but with tailings returned to the mine void rather than in tailings ponds at the surface.

- The model has enabled estimates to be made of the storage capacity required as a function of exceedence probability over the 30 year mine life under current climatic conditions.

- The probability that the pond volume proposed by ERA in the PER (810,000 m^3) would be exceeded over the life of the mine is about 1 in 1000. The pond volume required to achieve an exceedence probability of 1 in 10,000 over the life of the mine would be about 940,000 m^3.

Review of the hydrological model adopted by ERA

- The Supervising Scientist has reviewed the hydrological model adopted by ERA in the design of the water management system at Jabiluka. This review has resulted in a number of recommendations for improvement of the model.

- The effect on the volume of the water storage pond arising from the adoption of these recommendations is as follows:

  - The inclusion of interannual variability in evaporation and the inverse relationship between rainfall and evaporation leads to an increase in the required pond volume of about 3%.

  - The use of a simulated distribution of monthly rainfall rather than distributing annual rainfall to each month in fixed proportions determined from a typical distribution leads to an increase in the required capacity by about 1.7%.

  - The use of a more realistic distribution of ventilation system losses between the Wet and Dry seasons rather than a constant value for each month leads to an increase in the required capacity by about 1.2%.

  - The use of pan factors recommended in this review rather than those used by ERA in the PER results in an increase in the required volume of about 2.5%.

  - The use of a daily water balance model rather than a monthly model leads to an increase in required pond volume of about 1.4%.

  - The use of conceptual rainfall-runoff model rather than fixed runoff coefficients leads to a decrease in the required pond volume of about 0.4%.

- The combined effect of adopting the recommendations of this review on each of the above topics rather than the model used by ERA is that the pond volume required to achieve a given exceedence probability will increase by about 10%.

Use of pond evaporation rather than enhanced evaporation in the ventilation system
- The use of pond evaporation rather than enhanced evaporation in the ventilation system would lead to a reduction in the required storage capacity of about 30% because the full evaporative capacity would be available from the commencement of operations rather than achieving its maximum effect only after 10 years of operation.

- It is recommended that ERA, in its detailed design of the Jabiluka water management system, uses increased pond evaporation rather then enhanced evaporation in the ventilation system. In making this recommendation, it is recognised that some enhanced evaporation in the ventilation system as a result of dust suppression procedures is inevitable. This will need to be modelled carefully by ERA to achieve the optimum water management system.

- Partitioning the water retention pond into three or four compartments with connecting spill-ways and a water pumping system is one way in which control of evaporative losses could be achieved. Evaporative losses in dry spells could be minimised by pumping all remaining water into one of the compartments and could be maximised in wetter periods by using the full evaporative capacity of all of the compartments. It is recommended that ERA consider this approach in the detailed design of the water management system at Jabiluka.

Effect of climate change on the required storage capacity
- The minimum predicted temperature increase is the extreme scenario for water balance modelling since this would minimise evaporation and hence maximise the required storage volume. The minimum predicted increase of 0.35ºC over the next 30 years is insufficient to have any significant impact on evaporation. There is no need, therefore, to adjust the hydrological model to take the effect of temperature change into account.

- The maximum predicted change in annual rainfall from global warming over the next 30 years is 1%. There is, therefore, no need to repeat the simulation of the water management system to take this effect into account. The effect of climate change will be negligible.

- The effect of the predicted increase in storm intensity due to global warming has been assessed using the results of a sensitivity analysis. The results indicate that this increase in storm intensity would not have any significant impact on the required storage capacity of the water management system at Jabiluka.

Risk assessment of the ERA proposal
- A risk assessment has been carried out for the water management system proposed by ERA for the Jabiluka mine. In this context, it is important to note that tailings will not be stored at the surface. The principle hazard that needs to be assessed is the possible impact on people and on downstream ecosystems arising from the unplanned discharge of water that has been in contact with uranium ore.

- In conducting the risk assessment, estimates have been made of the concentraions of solutes in runoff from the ore stockpile. All of these concentrations are considered to be maximum expected values and some are likely to be significant over-estimates.

- The risk assessment included a contingency situation in which the accumulated runoff from the catchment of the water storage pond at Jabiluka exceeds the capacity of the pond and the excess water from the Total Containment Zone is diverted and allowed to flow freely to Swift Creek. Also assessed is the risk to the environment associated with structural failure of the water storage pond arising from overtopping of the pond, static failure of the constructed embankment, or the occurrence of a severe earthquake.

Risks associated with exceeding the available water storage capacity
- Estimates have been made of radiation exposure of members of the public resulting from an exceptional Wet season in which the storage capacity of the water retention pond is exceeded and the excess water is discharged to Swift Creek. The probability that any member of the public would receive a radiation dose of 20 µSv on one occasion during the 30 year life of the mine would be less than 1 in 10,000. The annual dose limit recommended by the International Commission on Radiological Protection for members of the public is 1000 µSv per annum. The conclusion is, therefore, that the water management system proposed by ERA for Jabiluka is one that poses an insignificant radiological risk to people living in the vicinity of the mine and consuming traditional foods obtained from the waterbodies downstream from the mine.

- Estimates have also been made of probable effects on aquatic animals resulting from an exceptional Wet season in which the storage capacity of the water retention pond is exceeded and the excess water is discharged to Swift Creek. The assessment included both radiological and chemical exposure. The conclusion reached is that, under normal circumstances, no effect on aquatic animals living in Swift Creek downstream from the Jabiluka mine would be expected to occur even when the volume of excess water discharged is that with an exceedence probability of 1 in 50,000 over the life of the mine. If the discharge results from an extreme rainfall event with an exceedence probability much greater than 1 in 100 at the end of a Wet season in which the rainfall has an exceedence probability of greater than 1 in 1000, some adverse effects may occur in invertebrates, but adverse effects on fish would not be expected. Any adverse effects on invertebrates would be very short-lived.

Risks associated with overtopping the water storage pond
- The probability of the pond overtopping in the absence of contingency measures has been estimated to be 5 in 10,000. It was assumed that overtopping would lead to complete structural failure of the pond embankment. The estimated radiation exposure of members of the public arising from such an event is about 150 µSv. Thus, even for this catastrophic event, the expected dose received by members of the public would not be greater than 15% of the annual limit recommended by the International Commission on Radiological Protection.

- The uranium concentration in Swift Creek following overtopping of the retention pond and subsequent total failure of the dam walls would be expected to give rise to adverse effects on some aquatic invertebrates in the Creek but adverse effects on fish would not be expected.

- There is a risk of about 5 in 10,000 that, following overtopping of the water retention pond, an area that is about 1% of the Magela floodplain would experience some adverse effects on aquatic animals. Fish and many other species would not be affected. Between about 2 km² and 20 km², adverse effects may persist but beyond 20km² no effects should be observed. In addition, any effects will be transitory and the system would fully recover following flushing by the natural waters of the Magela Creek.

- If a properly engineered spillway were installed in the wall of the retention pond, the dam would be protected from destruction under overtopping. This would result in the loss of much lower volumes of water over a longer period and would fully protect both Swift Creek and the Magela floodplain under the conditions considered here. It is recommended that such a spill-way be incorporated in the design of the retention pond.

Risks associated with slope failure of the embankment of the water storage pond
- The probability of slope failure is estimated to be less than the probability of overtopping which was estimated above to be about 5 in 10,000. Since slope failure would only arise under circumstances similar to those considered for overtopping, the estimates of environmental impact derived above for overtopping would also apply to slope failure.

Risks associated with a severe earthquake
- Over the period of the mine life, the probability of structural failure of the water retention pond arising from a severe earthquake has been estimated to be approximately 5 in 10,000. In deriving this estimate, only local and regional earthquakes were considered. The frequent but distant large earthquakes in the Banda Sea, Indonesia, should be considered in the design of a water retention pond since they give rise to many cycles of ground motion. It is recommended that ERA commissions such a study at the detailed design stage of the Jabiluka project.

- The risk of radiation exposure of members of the public resulting from such an earthquake would be extremely low. At the 1 in 10,000 level of probability, the estimated radiation exposure is about $30\,\mu Sv$. The highest calculated exposure, which is less than one tenth of the internationally accepted limit, has an extremely small exceedence probability.

- For an earthquake that occurs in the Wet season, the maximum area of the Magela floodplain in which adverse effects on some aquatic invertebrates might be expected is about 1.5 km^2 but the probability of this occurring is extremely small. The area affected at the 1 in 10,000 level of probability is less than 0.5 km^2 which is less than 0.3% of the floodplain area. At the same level of probability, residual effects may occur for some species of invertebrates out to an area of about 5 km^2. Even within these areas, the impact would be small (for example, fish should not be affected) and the system would fully recover following flushing by the natural waters of the Magela system.

- If an earthquake occurs in the Dry season, the area of impact would be greater. Nevertheless, the probability of such effects occurring remains very low and the system would recover during the following Wet season.

Contingency measures
- It is recommended that runoff from the ore stockpile should be isolated from runoff from the remainder of the Total Containment Zone so that it is always directed to the water retention pond while, under extreme conditions, runoff from the rest of the TCZ is diverted away from the storage pond. This measure would reduce still further the risk associated with exceeding the capacity of the storage pond.

- It is recommended that the water retention pond be constructed with a properly engineered spillway to ensure that, even if diversion contingency measures fail, the pond structure would not fail when the overtopping height is reached. This would reduce substantially the impact arising in the event of overtopping because only a small volume of water would be released to the environment rather than the full volume of the pond.

Long-term storage of tailings

Erosion of tailings in the long-term

- Once the Jabiluka mine is backfilled and sealed following completion of mining, the only mechanism for physical dispersal of the tailings solids will be erosion of the overlying bedrock. Since the mine void and the tailings silos will be about 100 m below the surface and the upper surface of these storage facilities will be below sea level, the whole land mass would need to be eroded away and by that time the wetlands of Kakadu would no longer exist. Thus, physical dispersal of the tailings does not pose a threat to the wetlands of Kakadu.

- The time required to erode the bedrock overlying the tailings in the mine void and the silos would be about 2 million years. Hence, the excess concentrations of all the radioactive progeny will have decayed away by the time the tailings are exposed and they will be in equilibrium with the residual uranium.

- Dispersal of tailings in the very long term will not constitute a hazard for future generations.

Hydrogeological features of the area

- The permeability of the Cahill Formation schists west of the orebody is significantly greater than that of the Kombolgie sandstone to the east. For this reason, it is recommended that the additional tailings silos should be excavated in the Kombolgie sandstone east of the orebody, as is currently planned by ERA. This choice of location will minimise potential environmental impacts.

- The excavation of the silos will result in additional material being placed on the surface. The location of the silos in the sandstone rather than in the schists to the west is also preferable from the perspective of minimising environmental hazards on the surface because the sandstone is relatively low in the concentrations of hazardous chemicals. This material will require additional attention during the rehabilitation phase, but control of potential impacts on surface waters will be straightforward.

- The quality of groundwaters in the vicinity of the Jabiluka orebody, both to the west in Mine Valley and to the east towards Swift Creek, is high. Soluble salt concentrations are relatively low and radionuclide concentrations are very low. It is concluded that there is very little movement of radionuclides into the groundwater aquifer from the orebody. In contrast, the groundwater underlying the acid sulphate soils of the Magela floodplain is of high salinity, is acidic, and has high sulphate concentrations. The observed natural sulphate concentrations are up to one third of the concentration of sulphate expected in the Jabiluka tailings.

Modelling of the dispersion of solutes in groundwater

- A two dimensional finite element model was used to determine flow directions, head distributions and the range of velocities.

- A three dimensional numerical solute transport model was applied to determine the concentrations of solutes leached from the tailings paste material for use as the source concentrations in an analytical model.

- An analytical contaminant transport model was used to determine concentrations due to advection, dispersion in three co-ordinate directions and retardation. This model used as input the range of velocities and source concentrations determined from the first two models. This model was combined with Monte Carlo calculations to determine

concentration profiles for a large number of different parameter values within selected ranges.

Properties and constituents of tailings

- Although limited information is available on Jabiluka tailings because the mine is not operational, physical properties of tailings at Ranger have been studied extensively. Ore at Jabiluka and at Ranger originate from the same geological formation and will be subject to the same milling process. Hence the tailings from the two mines are expected to have similar physical and chemical properties.

- Work undertaken as part of this review shows that achieving a tailings permeability of less than 10^{-9}m/sec is desirable. Based upon the research carried out on Ranger tailings, it is concluded that 99% of uncemented tailings in the silos at Jabiluka would have a permeability of less than 10^{-9}m/sec. Similar results are expected for tailings in the mine void but care will need to be exercised in placement of tailings in the mine void to avoid segregation and extensive residual voids.

- Research elsewhere on the effect of cementing the tailings paste indicates that the permeability of tailings will be reduced still further and may even reach permeabilities which are lower than normal tailings by a factor of 1000.

- The addition of cement to the tailings will result in highly alkaline conditions which will reduce the availability of metals and radionuclides for dispersion from the tailings mass in groundwater.

- The conclusion of this review is that there is a very high probability of achieving a permeability in the cemented tailings that is less than 10^{-9} m/sec.

Predicted concentrations of solutes in the environment

- Modelling of the concentrations of solutes in the deep aquifer east of the tailings repositories in the direction of Swift Creek predicts that, after 200 years, sulphate concentrations should not exceed 20 mg/L even at distances as short as 100 m from the repositories. Uranium is not expected to move more than 50 m in 1000 years and for radium this distance is 15 m. The maximum distance moved by uranium under the most extreme (and very low probability) scenario considered in the Monte Carlo analysis is 300 m. Concentrations of uranium and radium at these distances will be negligible compared to naturally occurring concentrations.

- The transport of solutes to the west of the repositories is expected to be more rapid because of the higher permeability of the schists compared to that of the sandstone. Monte Carlo calculations indicate a probable migration distance of 500 m after 200 years for non-reactive solutes including sulphate, although greater distances are possible. The tailings derived solutes would be entering an area of already very poor quality water where natural sulphate concentrations are in the range 1500 – 7000 mg/L so that the impact of the migration of water from the tailings repository would be negligible. In addition, the floodplain is underlain by low permeability clays which act to limit any potential upflow of the groundwater into surface waters.

- The Monte Carlo calculations indicate that uranium is likely to travel up to 200 m in a westerly direction in about 1000 years at which point the concentration would be reduced to less than 1 mBq/L, a concentration that is significantly less than natural concentrations in the region. The calculations show that migration of uranium by up to 1200 m is

possible but with a very low probability. It is concluded that radium and uranium will remain at background levels in the Magela floodplain.

- The groundwater modelling indicates that the upward component of groundwater flow is weak in both the groundwater movement to the east towards Swift Creek and to the west towards the Magela floodplain. The flow was found to be predominantly horizontal, implying that most of the solutes from the tailings repository will remain in the deep aquifer and move under the floodplain towards the sea and only a small fraction of the groundwater in the deeper aquifer would be accessible to surface waters. All of the calculated groundwater concentrations discussed above refer to concentrations in the deep aquifer. Surface aquifer concentrations arising from the tailings repositories will be negligible.

- The overall conclusion is that the wetlands of Kakadu will not be harmed as a result of the dispersal of tailings constituents in groundwater.

Risk assessment on the long-term storage of tailings

- A risk assessment of the probable impact on people and the wetlands of Kakadu National Park arising from the long-term storage of tailings in the mine void and the silos has not been carried out to the extent conducted for storage of uranium on the surface.

- To carry out such an assessment would require the extension of the analysis of groundwater dispersion to the quantitative prediction, using Monte Carlo analysis methods of the concentrations of solutes in the waters of the Magela floodplain and the probability with which these concentrations would occur. The range and quality of existing hydrogeological data do not enable such a detailed analysis to be carried out.

- However, the Monte Carlo analyses of solute concentrations in the deep aquifer and the information on the vertical component of groundwater flow demonstrate that the concentrations of the tailings derived solutes in surface waters of the Magela floodplain will remain at their natural values and will not be affected by dispersion of solutes from the tailings repositories.

General environmental protection issues

Protection of the environment in the Alligator Rivers Region

- The environmental protection regime that the Australian Government implemented for the mining of uranium at Ranger has been completely consistent with the principles of Sustainable Development and it has been demonstrated, through an extensive chemical, biological and radiological monitoring program, that no impact of significance under those principles has occurred, on either people or ecosystems of Kakadu National Park, throughout the operation of the Ranger mine.

- The same regulatory regime, but strengthened in some particular cases, would apply to the mining of uranium at Jabiluka.

The Ranger and the Jabiluka milling alternatives

- The Mission report was critical of ERA for proposing to proceed with the Jabiluka Mill Alternative (JMA) option 'despite not being the preferred environmental option'. This review, however, and the original assessment of the JMA proposal by Environment Australia have shown that, while the Ranger Mill Alternative (RMA) option is preferred, the risk to the environment arising from the JMA option is minimal and, in particular, that the wetlands of Kakadu National Park will not be threatened if the project proceeds.

Location and extent of the Jabiluka ore body

- The extent of the No 2 orebody at Jabiluka has not been fully delineated at depth in that section of the orebody to the east of the Hegge fault. If the Ranger Mill Alternative were to proceed, the mining at Jabiluka would be restricted to the currently delineated orebody and the period of mining would be about 30 years unless approval is given by the Commonwealth to mine any additional reserves following assessment under the *Environment Protection (Impact of Proposals) Act 1974.*

- If the Jabiluka Mill Alternative proceeds, there would be no need for further assessment of a proposal to mine additional reserves under the *Environment Protection (Impact of Proposals) Act 1974.*

Landscape-wide analyses

- Wasson et al (1998) suggest that the landscape context of the mine proposal has been inadequately addressed. The Jabiluka mine will be a point impact, with some specific potential effects, which are addressed in the main body of this report and shown to be negligible. It is simply not true to suggest that the EIS and PER are inadequate because they have not considered potential impacts across the whole of Kakadu National Park. The assertion that the context modelling for the minesite need be broader than is currently the case is therefore rejected.

Acid sulphate soils

- The concerns of Wasson et al (1998) that heavy metals accidentally released from the mine site could be mobilised into downstream ecosystems by the acid sulphate soils and that the pumping of water from a billabong could lead to increased acidity in surface waters are not justified. Experience at the Ranger mine has shown that in every case where accidental releases have occurred, the total load of any metals released is extremely small compared to the natural load of metals in the soils of the floodplain. The previous proposal to re-establish the old Ja-Ja camp has been withdrawn and there are no plans to pump large quantities of water from the billabong.

Rehabilitation of the Jabiluka lease area

- ERA is required to rehabilitate the Jabiluka mine site in a manner which will establish an environment in the lease area that reflects, to the maximum extent that can reasonably be achieved, the environment existing in the adjacent areas of Kakadu National Park. The intention is that the rehabilitated area could be incorporated into the Kakadu National Park without detracting from park values.

- The Government has established secure mechanisms to ensure that these rehabilitation objectives will be achieved even if the company becomes insolvent and ceases operations prior to the completion of adequate rehabilitation of the site.

Transport of uranium from the Jabiluka mine

- The transport of uranium product from Jabiluka to the Port of Darwin through Kakadu National Park is governed by laws of the Northern Territory which include the total text of the International Atomic Energy Agency Regulations for the Safe Transport of Radioactive Material.

- Two emergency trailers and trained emergency response crews are on call for each consignment of uranium product. The trailers contain equipment that would allow the crew to safely collect any spilled uranium product. The hazards associated with spillage of uranium product have been carefully assessed and emergency procedures have been

developed to ensure that both people and ecosystems will be protected in the event of an accident.

- There has never been a transport accident involving the release of uranium product during the life of the Ranger mine.

1.4 Conclusions

This report has been prepared in response to the request of the World Heritage Committee that the Supervising Scientist conduct a full review of scientific issues raised by the Committee's Mission to Kakadu National Park in October–November 1998. Perceived scientific uncertainty with respect to these issues had led to the Mission's conclusion that the natural values of Kakadu are threatened by the Jabiluka project.

It must be emphasised that this report does not purport to be a complete environmental impact assessment of the Jabiluka project. There are many environmental protection issues related to the development of Jabiluka that were not raised in the Mission's report or in the decision of the World Heritage Committee. These broader issues have already been addressed in the environmental impact assessment process to which the Jabiluka project was subjected and are covered by the requirements that the Commonwealth Government imposed in granting its approval for the project to proceed.

This report includes a thorough review of all of the issues raised by the World Heritage Committee and provides a detailed assessment of the risks to people living in the vicinity of the mine and the risks to the wetlands of Kakadu arising from the storage of uranium ore at the surface at Jabiluka, the management of water and the storage of tailings.

Many of the issues that were raised by the report of the Mission of the World Heritage Committee come into the category of detailed design. That is, many of the issues had been identified by the Supervising Scientist and others as being issues that would need to be resolved by the proponent in consultation with officials of the Northern Territory and the Supervising Scientist at the detailed design stage but the conclusion had been reached that there were no insurmountable obstacles that would prevent a design being achieved that would ensure the highest level of environmental protection in Kakadu National Park.

This detailed review has demonstrated that there were a number of weaknesses in the hydrological modelling presented by ERA in the EIS and the PER. Accordingly, a number of recommendations have been made which should be implemented by ERA in completing the detailed design of the Jabiluka project. On the other hand, the review has demonstrated quite clearly that, if the design of the water management system proposed by ERA in the PER *had* been implemented, the risk to the wetlands of Kakadu National Park, and the risk of radiation exposure to people of the region would have been extremely low. This conclusion is valid even in extreme circumstances leading to the complete failure of the structure of the water retention pond at Jabiluka.

The lay reader will, no doubt, find this conclusion surprising. Its origin, however, lies in the fact that uranium is not a particularly toxic substance for aquatic animals. It has been well established that the toxicity of uranium is much lower than that of many more common substances such as copper, cadmium and lead. It is the perception of the public that uranium is a very dangerous substance, and the failure of the scientific community to persuade the public otherwise, that has led to adoption of extreme measures to ensure that no amount of uranium should leave the site of a uranium mine.

Similarly, uranium in its natural state does not pose a particularly severe radiation threat. Exposure to uranium and its radioactive progeny needs to be controlled but the inherent radioactivity of uranium and its progeny is sufficiently low that ensuring that people do not receive exposures that would be harmful is relatively straightforward. It is only when uranium is used as fuel in a reactor that fission reactions result in a large number of radioactive products which produce high levels of ionising radiation.

Thus, on scientific grounds, there is no reason why water collected at Jabiluka could not be discharged into the surface waters of the Magela floodplain under a suitably designed control regime that would protect both people and ecosystems. The proposal by ERA that these waters should be totally contained at the mine site was made in response to social concerns and perceptions, not scientific evidence.

The long-term threats to the wetlands of Kakadu arising from the storage of uranium mill tailings at Jabiluka have also been assessed. Because the tailings will be stored at a significant depth below the surface of the land, physical dispersion of the tailings will not be possible for millions of years. The whole land mass would need to be eroded away and by that time the wetlands of Kakadu would no longer exist. Even then, the threat to future generations is insignificant because the residual uranium and its radioactive progeny would be present at low concentrations and would be mixed, when dispersed, with the inert material surrounding the current orebody. Dispersion of radionuclides and other constituents of the tailings in groundwater has been shown to present no threat to the wetlands of Kakadu or the people who live there in either the short-term or the long-term.

The conclusion of this review, therefore, is that, contrary to the views expressed by the Mission, the natural values of Kakadu National Park are not threatened by the development of the Jabiluka uranium mine and the degree of scientific certainty that applies to this assessment is very high. There would appear, therefore, to be no justification for a decision by the World Heritage Committee that the natural World Heritage values of Kakadu National Park are in danger as a result of the proposal to mine uranium at Jabiluka.

2 Introduction

2.1 Mining of uranium in the Alligator Rivers Region

In April 1975, the Commonwealth Government of Australia established a public inquiry, the Ranger Uranium Environmental Inquiry (RUEI), into the proposal to mine uranium at the Ranger site in the Alligator Rivers Region of Australia's Northern Territory (fig 2.1). This wide ranging Inquiry examined generic issues of the nuclear fuel cycle, including waste disposal and possible dangers of nuclear weapons proliferation, as well as site specific aspects of the proposed Ranger development, including protection of the local environment and Aboriginal land rights.

In August 1977, following the publication of the findings of the RUEI, the Government announced its decision to authorise the mining and export of uranium in the Alligator Rivers Region under the very strict requirements for environmental control recommended by the Inquiry.

Essential elements of the plan adopted by the Commonwealth Government to protect the environment and to insulate, to some extent, the Aboriginal people of the Region from the social disruptions inevitably associated with such a major development, were:

- the granting of land to the traditional owners under the *Aboriginal Land Rights (Northern Territory) Act 1976*,

- the establishment of Kakadu National Park, part of which comprised Aboriginal land leased back to the Commonwealth Government for the purposes of the Park, and

- the establishment of a Supervising Scientist to assist in the development of measures for the protection of the environment and oversee their implementation.

From the outset, existing exploration and mining leases at Ranger, Jabiluka and Koongarra were excluded from the Park.

Following the Government's decision, approval was given for the mining of uranium at Ranger and, after a period of mine construction, mining and milling of uranium commenced in 1981. Mining of Orebody No 1 was completed in 1994 while mining of Orebody No 3 commenced in May 1997 and should be completed by about 2007. (The smaller No 2 orebody is close to Mount Brockman, an Aboriginal sacred site, and will not be mined.)

In October 1996, Energy Resources of Australia submitted a Draft Environmental Impact Statement (EIS) (ERA 1996) for the mining of uranium at the Jabiluka site, 25 km north of Ranger. This proposal was assessed by the Commonwealth Government under the *Environment Protection (Impact of Proposals) Act 1974*, (EPIP Act). The principal proposal, known as the Ranger Mill Alternative (RMA), involved the mining of the Jabiluka orebody by underground methods and the milling of the ore at the existing mill at Ranger. This proposal received approval from the Commonwealth Government in October 1997 subject to a broad range of requirements on environmental protection. However, the RMA proposal requires the trucking of ore from Jabiluka to Ranger and this requires the specific agreement of the Aboriginal land owners. The traditional land owners have so far refused to give their permission for the milling of Jabiluka ore at Ranger.

The draft EIS also contained an alternative proposal, known as the Jabiluka Mill Alternative (JMA), which involved the construction of a new mill at Jabiluka. The conclusion of the Commonwealth Government on the JMA in October 1997 was that insufficient information had been presented for a rigorous assessment of environmental impact and that, should ERA
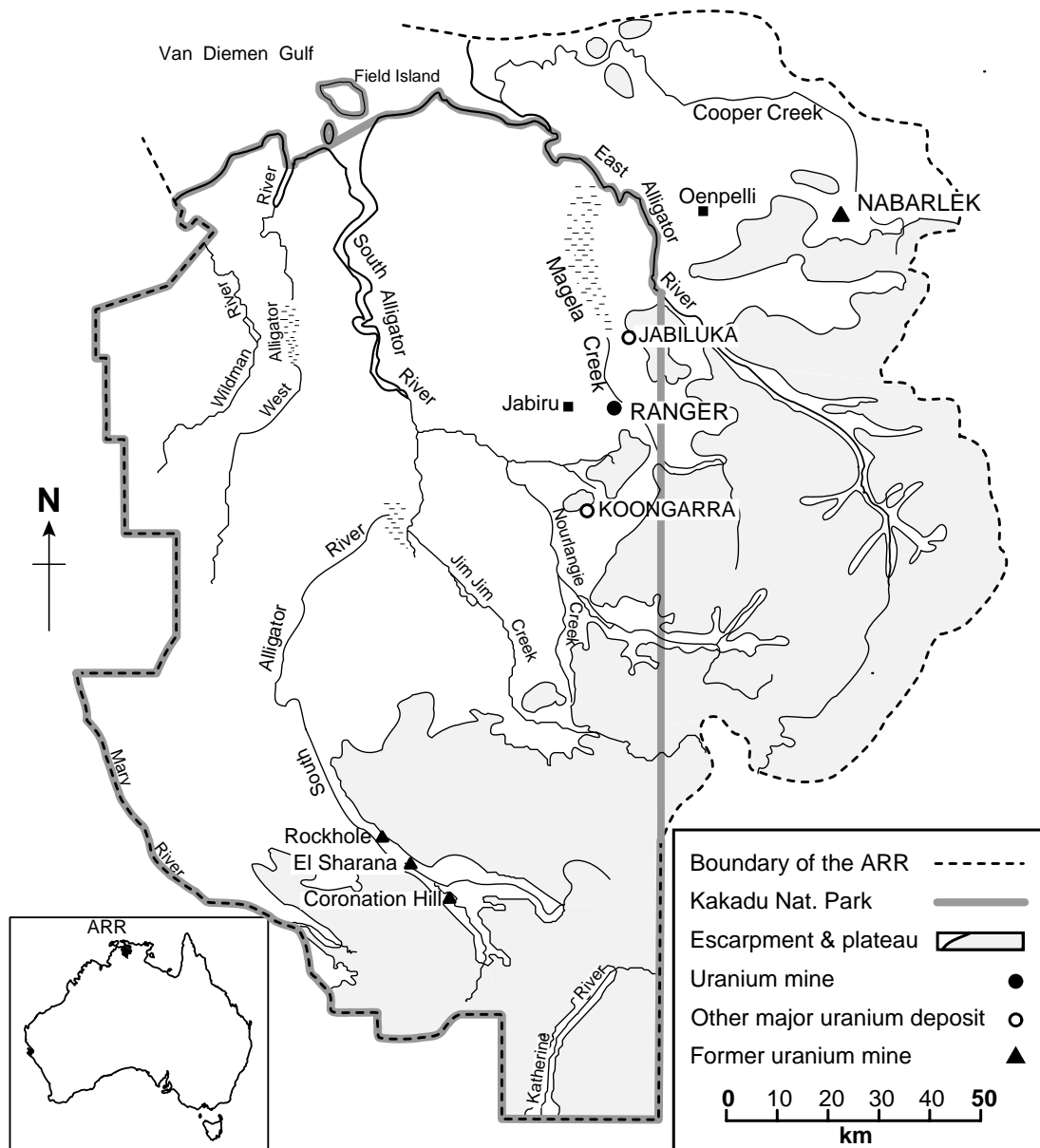
Figure 2.1 The Alligator Rivers Region in Australia's Northern Territory. The boundary of Kakadu National Park, within the Region, is indicated.

wish to proceed with that proposal, a further assessment under the EPIP Act would be required.

In June 1998, ERA submitted a Public Environment Report (PER) (ERA 1998) containing its detailed proposal for the milling of ore at Jabiluka. Following assessment of the proposal under the EPIP Act, the Government approved the project in August 1998 subject to a number of environmental requirements. Principal among these was the requirement that all mill tailings would be returned underground to the mine void and to specially constructed stopes or silos instead of tailings pits as proposed by ERA in the PER.

2.2 World Heritage Bureau Mission to Kakadu

At the twenty-second meeting of the World Heritage Committee, held in Paris from 22 to 27 June 1998, a decision was reached that the Chair of the Committee should lead a mission to Australia and Kakadu National Park to assess any ascertained or potential threats to the World Heritage values of Kakadu National Park that might arise from the proposal to mine uranium at Jabiluka. The visit of the Mission took place from 26 October 1998 to 1 November 1998.

The report of the Mission was submitted to the Bureau of the World Heritage Committee at its meeting held in Kyoto, Japan, on 27–28 November 1998. The report concluded that the development of the Jabiluka mine poses both ascertained and potential dangers to the cultural and natural values of the World Heritage property. These threats were elaborated in sections 7.5 to 7.17 of the report. Section 7.5 referred to scientific uncertainties and is quoted in full below.

> *7.5   Scientific uncertainties and the need for risk assessment*
>
> *There are three issues of scientific uncertainty that lead to a finding of potential danger: (i) the degree of uncertainty concerning the quality of the hydrological modelling carried out in designing the water management plan for the mine site and the implication that this may lead to the release of water from the mine site into the Swift Creek system; (ii) the degree of uncertainty concerning the effectiveness of the concrete pasting process as a means of storing the tailings in the mine void, and (iii) the possible impacts on catchment ecosystems.*
>
> *The mission received extensive briefings from ERA and the Supervising Scientist Group (SSG). The mission recognizes the scientific analyses carried out by ERA and the valuable role and work of the Supervising Scientist Group (SSG). However, in the light of the concerns expressed by some of Australia's most authoritative and widely respected scientists and the uncertainty that these concerns raise, the mission is of the view that 'best practice' is not to continue mining at Jabiluka regardless of the concerns, but rather to apply the Precautionary Principle which requires that mining operations at Jabiluka be ceased.*
>
> *There is also uncertainty expressed by ERA over the location and extent of the uranium ore body at Jabiluka and the consequent uncertainty over the final scale and duration of the Jabiluka mine. This uncertainty combined with the scientific concerns adds to the conclusion that the property is faced with a potential danger as defined in Paragraph 79 (ii) of the Operational Guidelines.*
>
> *Given the uncertainties mentioned above, the mission notes that formal risk assessments should have been undertaken for the Jabiluka mining proposal. Risk assessment processes are capable of putting solid upper-limit probability factors against the*

various environmental risks; and the mission considers this essential to conveying a realistic picture of the likely overall impact of the mine.

Recommendation 2*: The mission noted the serious concerns and preoccupations expressed by some of Australia's most eminent scientists as to the unacceptably high degree of scientific uncertainties relating to the Jabiluka mine design, tailings disposal and possible impacts on catchment ecosystems. The mission shares these concerns and therefore recommends application of the Precautionary Principle which requires that mining operations at Jabiluka be ceased.*

The report of the Mission to Kakadu was considered by the Bureau of the World Heritage Committee at its meeting at Kyoto, Japan, on 27–28 November 1998. The Bureau endorsed the report and noted, *inter alia*, the significant difference in opinion concerning the degree of certainty of the science used to assess the impact of the Jabiluka mine on the World Heritage values of Kakadu National Park. It recommended that the Committee seek a report on these issues from the Supervising Scientist.

2.3 Decision of the World Heritage Committee

The World Heritage Committee considered the report of the Mission and the recommendations of the Bureau of the World Heritage Committee at its meeting in Kyoto on 30 November – 5 December 1998. The full text of the decision of the Committee is given in Appendix 1. The sections of the decision relevant to scientific uncertainty are given below.

The Committee

noted that there is significant difference of opinion concerning the degree of certainty of the science used to assess the impact of the mine of the World Heritage values of Kakadu (notably hydrological modelling, prediction and impact of severe weather events, storage of uranium ore on the surface and the long-term storage of the mine tailings);

and decided that:

*The Australian authorities be requested to direct the Australian Supervising Scientist Group to conduct a full review of the scientific issues referred to in Paragraph (iv) above, to be provided to the Secretariat by **15 April 1999**. The review will be submitted to peer review by an independent scientific panel composed of scientists selected by UNESCO in consultation with the International Council of Scientific Unions and the Chairperson of the World Heritage Committee. The report of the peer review will be provided to the Secretariat by **15 May 1999** for immediate distribution to the members of the Bureau, IUCN and the Australian authorities.*

The current report from the Supervising Scientist is in response to the above request.

2.4 Scope of this report

The four issues raised in the Committee's decision are, in some cases, clearly related to issues raised in the report of the Bureau Mission to Kakadu National Park and to issues raised in the submission by Professor Wasson and others to the Mission (Wasson et al 1998). In other cases, the precise definition is less clear. For this reason the Supervising Scientist wrote to the Chair of the World Heritage Committee seeking clarification on the precise description of these technical issues to ensure that there would be no misunderstanding at a later date.

The four issues specified in the decision are listed below together with a longer description of each issue that represents the Supervising Scientist's interpretation of what is meant by each.

Hydrological modelling

This topic includes issues raised by Wasson et al (1998) in section 5 of their submission; in particular, (i) the estimate of what constitutes a 1 in 10,000 annual exceedence probability (AEP) rainfall for the purpose of designing the retention pond, (ii) evaporation in the exit stream of the mine ventilation system and (iii) evaporation from open water.

Prediction and impact of severe weather events

This topic refers to (i) uncertainties raised by Wasson et al (1998) in section 4 of their submission arising from the work of Nott (1996) about high discharges in the Waterfall Creek region and the Katherine floods, (ii) uncertainties expressed by Wasson et al (1998) on what constitutes a Probable Maximum Precipitation event and (iii) the effect of climate change on both mean annual rainfall and the intensity of storms.

Storage of uranium on the surface

Included under this topic are (i) the design of the surface facilities to ensure, taking into account issues raised in the first two topics above, that runoff from the ore stockpile will all be collected by the retention pond even under extreme weather conditions and (ii) the adequacy of parameters used in the design of the retention pond to ensure containment of water collected in it under extreme weather conditions without the need to release water to the surface water system beyond the mine site.

Long-term storage of the mine tailings

This topic includes two issues related to the long term containment of 100% of the tailings at Jabiluka in the mine stopes and additional stopes/silos excavated near the ore body specifically to contain tailings. The two issues are (i) long-term containment of the solid tailings so that they do not represent a threat to the wetlands of Kakadu and (ii) dispersal of contaminants in groundwater from the contained tailings and their consequent potential impact on the wetlands of Kakadu.

The Chair of the World Heritage Committee has confirmed that analyses of these issues should be addressed in the Supervising Scientist's report along with the analysis any other issue that, in the view of the Supervising Scientist, will be necessary for the Committee to reach a decision.

Although the Supervising Scientist has a broad range of expertise available within his own organisation, given the intense interest in the World Heritage issue and the need for absolute transparency, independent expert advice within Australia was sought on the following topics to assist the Supervising Scientist in his review of the topics identified by the World Heritage Committee:

(i) **Hydrometeorological analysis** to determine rainfall figures appropriate for the design of a water management system at the Jabiluka mine,

(ii) **Impact of climate change** on parameters for the design of surface runoff storage facilities at Jabiluka,

(iii) Determination of the **water storage capacity** needed to meet the specified environmental protection standard, and

(iv) **Groundwater modelling** to determine the probable increase in surface water concentrations of specified chemical constituents leached from tailings.

The reports on these consultancy projects are included as attachments to this report. The Supervising Scientist's interpretation of the material contained in these reports, and the

analysis of issues by the staff of the Supervising Scientist, provide the basis for this current report.

Following this introductory chapter, the four principal topics identified by the World Heritage Committee are addressed in chapters 3, 4, 5 and 6. In addition, other issues that the Supervising Scientist believes require clarification are addressed in chapter 7. The overall conclusions of this review are presented in chapter 8.

3 Hydrological modelling

3.1 Introduction

A number of questions were raised by Wasson et al (1998) on the validity of the assumptions and analytical methods used by the proponent in the design of the Total Containment Zone (TCZ) at Jabiluka. The issues raised relate to:

- The methods used to derive the annual rainfall that is not likely, on average, to be exceeded more than once in 10,000 years (the 1:10,000 AEP annual rainfall),

- The methods used to estimate evaporation in the water retention pond, and

- The calculation of the quantity of water that will be evaporated in the exit stream of the mine ventilation system.

Various aspects of these issues were raised in the Supervising Scientist's submissions on the Jabiluka EIS and the PER. They were, however, raised in the context of issues that would need to be addressed at the detailed design stage of the project if the approval for mining were to be granted. The important issues at the EIS/PER stage are:

(i)   the acceptance of a **design criterion**, that the water retention system should capture and retain all water that could accumulate in a year where the annual rainfall is that which is not likely, on average, to be exceeded more than once in 10,000 years, and

(ii)   that adequate evidence is presented that this design is achievable.

The Supervising Scientist reached the conclusion that such a design is achievable and that outstanding detailed technical issues could be resolved by the Supervising Authorities and the Supervising Scientist in the normal process of assessment and authorisation if approval for the project was given. This approach was endorsed by Environment Australia in its assessment of the EIS and PER.

The above hydrological issues are addressed in this chapter to determine the basic parameters required for design of the water management system under current climatic conditions. Issues related to possible climate change are addressed in chapter 4 and design issues *per se* are addressed in chapter 5.

3.2 Determination of 1 in 10,000 year annual rainfall

The design criterion adopted by ERA in the Draft EIS (ERA 1996) for the retention pond in the Total Containment Zone (TCZ) at Jabiluka was that it should be capable of retaining the runoff from the TCZ in a 1:10,000 AEP rainfall year as well as including a residual volume of water retained from previous years (ERA 1996, page 4–68). Thus the estimate used for the 1:10,000 AEP rainfall was considered an important issue for the success of the total containment strategy.

3.2.1 Choice of data sets

The first issue that needs to be addressed in estimating the 1:10,000 AEP annual rainfall is the choice of data set(s) to be used in the analysis. Data are available for Jabiru airport, 18 km south of Jabiluka, for the period from 1971 until 1998, a relatively short data set, and for Oenpelli, about 25 km north east of Jabiluka, from 1911 until 1998. (For locations, see fig 2.1.) The records for all other meteorological data sites within 100 km are relatively short. Extensive data sets (of the order of 100 years) are available for Darwin, Katherine, Pine Creek and a number of other sites but they are all more than 200 km distant from Jabiluka.

The Alligator Rivers Region, in common with much of far northern Australia, has a tropical monsoon climate. Virtually the entire rainfall occurs in the Wet season which varies in length but is generally confined to the December – March period; November and April tend to be transitional months. The Dry season extends from about May to September. For this reason, the rainfall year considered in this report is defined to be from September of one year until August of the following year.

In 1988, the Supervising Scientist carried out an analysis (Carter 1990) of the correlation between the Jabiru rainfall record and the records for a number of sites in the north of the Northern Territory. The correlation was found to be best for Oenpelli and this data set was used to determine the 1:10 and 1:100 AEP annual rainfall values for the Ranger mine site. A significant limitation of the Jabiru data set was the very short length of record, 17 years. The additional data gathered in the last 10 years has significantly extended the Jabiru data set and a further comparison is warranted.
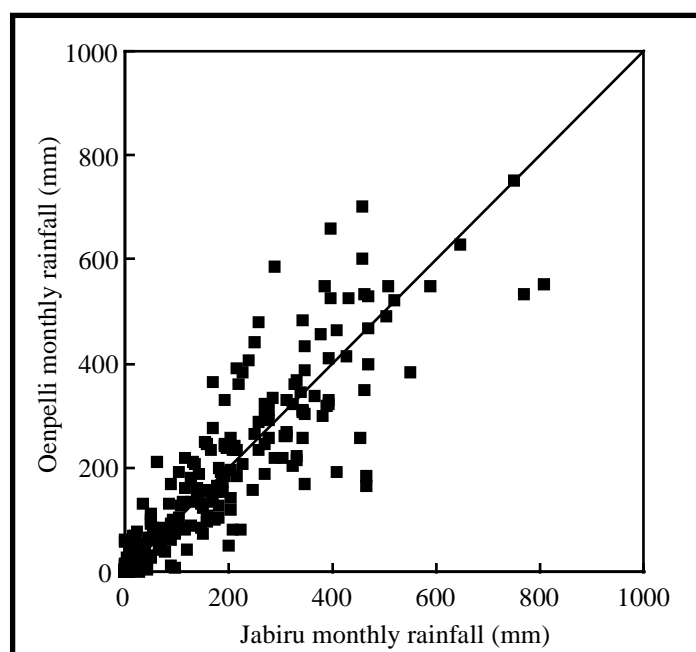
Figure 3.2.1 Comparison of monthly rainfall at Jabiru and Oenpelli
(data from Sep 1971 to Aug 1998)

Table 3.2.1 Comparison of annual rainfall statistics for Jabiru and Oenpelli from September 1971 until August 1998

	Jabiru (mm)	Oenpelli (mm)
Mean annual rainfall	1483	1,500
Standard deviation	302	295
Standard error	58	57

An analysis of the extended data set has now been carried out by the University of Melbourne (Chiew & Wang 1999, Attachment D) using data supplied by the Bureau of Meteorology (1999) (Attachment B). For the period of coincident records (September 1971–August 1998) the mean rainfall, standard deviation and standard error in the mean are given in table 3.2.1. This comparison shows excellent agreement between the two stations. Chiew and Wang

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(1999) also examined the correlations between the two stations for monthly rainfall, annual rainfall and daily rainfall characteristics. For example, the correlation for monthly rainfall is shown in figure 3.2.1. The correlation coefficients found for the Wet season months were 0.79 for December–February and 0.92 for March–May. Overall the correlation is very good and the conclusion drawn by Chiew and Wang (1999) is that the Oenpelli data set should, because of the much longer record, be used for estimating the 1:10,000 AEP annual rainfall and for other hydrological modelling for the Jabiluka project. This conclusion is supported by the Bureau of Meteorology (1999).

The long-term (1917–1998) statistics for annual rainfall at Oenpelli are given in table 3.2.2 (Bureau of Meteorology 1999). The long-term mean annual rainfall, 1397 ± 30 mm, is significantly lower than the value of 1500 mm given in table 3.2.1 for the shorter record between 1971 and 1998. Carter (1990) used a *cusum* technique to examine long-term cycles or trends in the mean annual rainfall at a number of meteorological stations in the Northern Territory. The *cusum* method (Cumulative Sum) computes the sum, at any time in a time series, of the difference between the current observed value of a variable and the long-term mean value. This analysis revealed that the period between the mid-1960s until the mid-1980s was one of significantly higher average rainfall than the long-term mean. This conclusion was valid for the stations at Darwin, Oenpelli, Pine Creek and Katherine. Hence the short-term record for Oenpelli, which is dominated by this period of higher than average rainfall, has a mean annual rainfall greater than the long-term mean. This conclusion is also likely to be true for Jabiru. Incorporation of this decadal-scale variation in rainfall into the design of the Jabiluka water management system is considered in chapter 4.

Table 3.2.2 The annual characteristics of Oenpelli rainfall data

Statistic	Magnitude	Standard Error
Mean (mm)	1397	30.3
Standard deviation (mm)	284.5	21.4
Coefficient of skewness	-0.018	0.257

3.2.2 Estimation of the 1:10,000 AEP annual rainfall for Jabiluka

The Bureau of Meteorology (1999) notes that the coefficient of skewness of the annual rainfall series is small and that, therefore, the normal distribution is appropriate to describe the data. The annual rainfall data for Oenpelli and the fit to the data using a normal distribution are shown in figure 3.2.2. The x-axis in this graph has a normal probability scale and plotting position is determined by the rank of annual rainfall (plotted on the y-axis). Data that are normally distributed plot as a straight line on this type of graph. Chi-squared (χ^2) test results (test statistic – 4.39/chi-square value (0.05%) – 9.49) and Kolmogorov Smirnov test results (test statistic – 0.05881/value – 0.145) indicate that the annual rainfall data series for Oenpelli is normally distributed. This conclusion is consistent with that of the Supervising Scientist (Vardavas 1992) who examined the distributions of annual rainfall data for several meteorological stations in the north of the Northern Territory. Vardavas (1992) concluded on the basis of a χ^2 analysis that the data for Darwin and Oenpelli were better described by a normal distribution than by a log-normal distribution. For these reasons, a normal distribution has been assumed in the estimation of the 1:10,000 AEP rainfall for Oenpelli.

For a normal distribution, the probability of exceeding a particular value of the variable *x* is given by

$$P(x \geq x_0) = 1 - F(x_0)$$

where F(x) is the cumulative distribution function for a normal distribution. From Institution of Engineers, Australia, (1987), $F(x_0) = 0.0001$ when

$$x_0 - \mu = 3.719\sigma$$

where μ and σ are the mean and standard deviation of the distribution. Hence, using the data in table 3.2.2, the Bureau of Meteorology conclude that the 1:10,000 AEP annual rainfall estimate for Oenpelli is 2455 mm with a standard error of 85 mm. The 95 % confidence limit for this estimate, rounded to the nearest 10 mm is 2460 ± 170 mm.
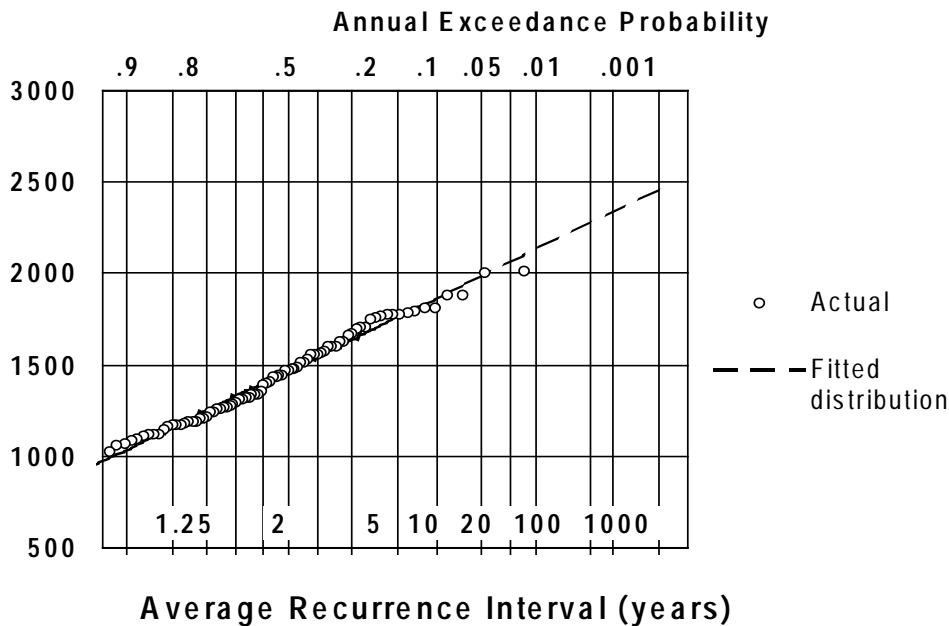
Figure 3.2.2 Distribution of annual rainfall for Oenpelli

The Bureau of Meteorology (1999) notes that an alternative method of calculating annual exceedance probability (AEP) from a relatively short record is to calculate the expected probability (Institution of Engineers, Australia, 1987, Beard 1960). Here, 'expected' is used in the statistical sense and the name would be more precisely expressed as 'Expected Annual Exceedance Probability'. This approach takes the view that one record, such as the Oenpelli record, is just one sample from a normally distributed population, and it can be shown that, on average, over a large number of samples, the expected probability of estimates of the 1 in Y AEP event is always greater than 1 in Y. This implies a higher annual rainfall because it is the rainfall for the expected probability rather than that for the sample probability. The concept is a complex one and the subject is still debated in the literature. However, if the procedures recommended by Beard (1960) are followed, the estimate of the 1 in 10,000 year annual rainfall for Oenpelli is 2,510 mm. This estimate is not significantly different from the 2,460 mm recommended.

The recommended value of the 1:10,000 AEP annual rainfall is in very good agreement with the value adopted by ERA in the Draft EIS, namely 2450 mm. The rationale adopted by ERA in deriving this estimate is described in the Supplement to the Draft EIS (page 5–22). ERA

used the Jabiru rainfall data because (as noted above) the mean annual rainfall for Jabiru is greater that the long-term mean for Oenpelli and this approach should yield a conservative result. However, the highest recorded rainfall in 1975–76 was attributed to an average recurrence interval of 85 years based upon the observation that this rainfall was higher than any that had occurred in the 85 year record at Oenpelli. In support of this approach, ERA also pointed out that the 1:10,000 AEP derived from the Oenpelli record is 2461 mm (using data up to 1996). The Bureau of Meteorology (1999) provides the assessment that while there is no statistical evidence for treating the 1975/76 Jabiru rainfall as an outlier, the fact that Oenpelli also experienced it's highest annual rainfall report on record in 1975/76 provides some physical justification for reassigning its plotting position. Thus, the validity of the approach adopted by ERA may be questioned, but there is justification for the approach and the outcome was that, essentially, the Oenpelli 1:10,000 AEP was adopted, which is in agreement with the conclusion of this report.

The 1:10,000 AEP annual rainfall was also estimated by Chiew and Wang (1999) who used a stochastically generated daily rainfall distribution based upon the Oenpelli rainfall record. The result obtained was 2702 mm, a value that is higher than that recommended by the Bureau of Meteorology (1999) by almost three standard errors. Chiew and Wang (1999) argue that the difference is attributable to model dependence which is not taken into acount in the error estimated by the Bureau of Meteorology (1999). However, while the observed skewness of the daily rainfall data is well reproduced in Chiew and Wang's model, the modelled skewness in the annual data is 0.37 compared to the observed value of –0.018 ± 0.257. The positive skewness of the stochastically generated data will lead to higher predictions for rainfall in extremely wet years.

In summary:

- It is recommended that the Oenpelli rainfall record for the years 1917 to 1998 should be used for estimating the 1:10,000 AEP rainfall and for other hydrological modelling for the Jabiluka project because it is much more extensive than that at Jabiru and is consistent with the Jabiru record in the period of overlap.

- The recommended value for the 1:10,000 AEP rainfall is 2460 mm with 95% confidence limits of ±190 mm. This estimate is in very good agreement with the value adopted by ERA, 2450 mm.

- It is acknowledged that there may be some residual model dependence in the recommended value for the 1:10,000 AEP rainfall. However, this is not important for modelling of the Jabiluka water management system in this review because a Monte Carlo simulation method is used based upon stochastically generated rainfall data.

3.3 Evaporation from open water

Wasson et al (1998) raise two issues related to the credibility of ERA's estimates of water losses by evaporation in the water retention pond at Jabiluka. These issues are:

- the appropriateness of the pan factors used to convert observed Class-A pan evaporation measurements to pond evaporation estimates, and

- the significance for water balance modelling of the failure to take into account the inverse relationship between evaporation and rainfall

3.3.1 Pan factors

Wasson et al (1998) note the use by ERA of two simple seasonal factors to estimate pond evaporation from pan measurements; 0.6 in the Dry season (May–October) and 0.75 in the Wet season (November–April). They assert that there is a need to check these factors by appropriate modelling that incorporates existing solar radiation data and that the extensive evaporation study conducted at Manton Dam, south of Darwin, needs to be taken into account.

The approach outlined above was adopted by ERA in the draft EIS in 1996 but Wasson et al (1998) seem to have been unaware that ERA adopted a more sophisticated approach in the PER for the Jabiluka Mill Alternative. It was the proposal for the Jabiluka Mill Alternative, presented in 1998, which was the subject of investigations conducted by the Mission of the World Heritage Committee to Kakadu. ERA outlined in Appendix B1 of the PER the procedure adopted in estimating evaporation from the retention pond. Pan factors for each month of the year were adopted following a review of all existing evaporation data relevant to the region by CSIRO (Hatton 1997). The conclusion of Hatton (1997) was that, with the exception of the two months of April and October, the pan factors derived by the Supervising Scientist (Vardavas 1987) should be used in all water balance calculations.
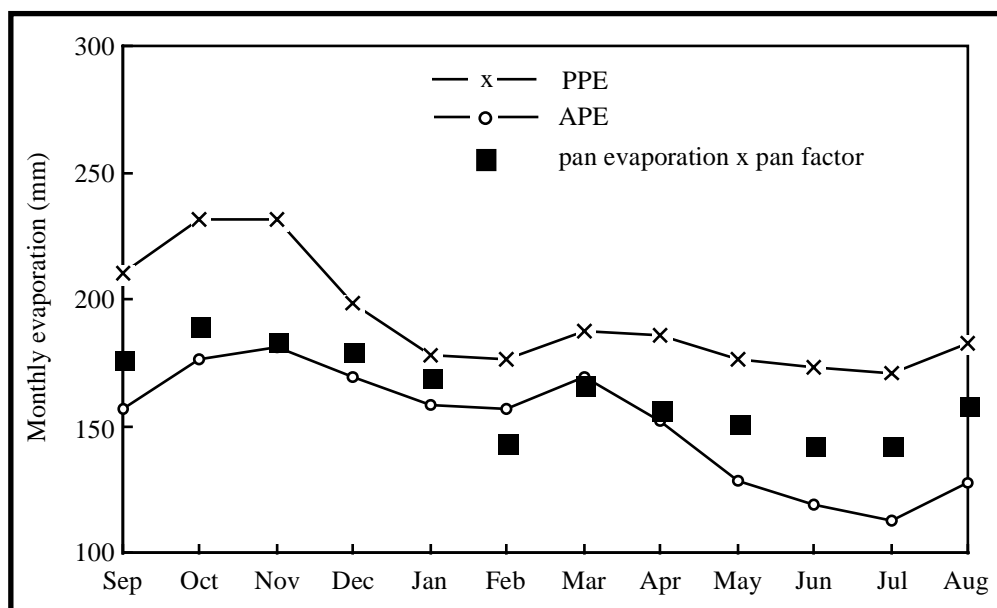
Figure 3.3.1 Comparison of average monthly storage evaporation estimates and point potential and areal potential evapotranspiration rates

Vardavas (1987) modelled the seasonal variations of net solar and net terrestrial radiation and evaporation for water bodies in the wet-dry tropics of northern Australia. The input to the model consisted of short-term and long-term average meteorological data describing the seasonal changes in atmospheric conditions. He compared his calculations of radiation and evaporation with those determined in the 2-year field study at Manton Dam and 15 years of solar radiation measurements at Darwin and found excellent agreement between his calculations and the measured variables. He then applied the model to the specific case of evaporation from ponds at the Ranger mine at Jabiru. Hence, all of the suggestions of Wasson et al (1998) had already been taken into account in the evaporation calculations presented by ERA in its hydrological modelling of the water management system for the

Jabiluka project and the scientific information underlying the modelling was based upon previous work of the Supervising Scientist.

Despite this, a further investigation of this issue was sought by the Supervising Scientist as part of this review. The University of Melbourne (Chiew & Wang 1999) re-examined the appropriateness of the pan coefficients proposed by Hatton (1997). The average monthly evaporation rates derived using these coefficients were compared with point potential evapotranspiration (PPE) and areal potential evapotranspiration (APE) estimates. The PPE and APE estimates were extracted from the digital maps of evapotranspiration of Australia prepared by the Cooperative Research Centre for Catchment Hydrology. In simple terms, the PPE is the rate of evapotranspiration from a small wet area in an existing environment, while the APE is the rate of evapotranspiration if a large area is well watered. The storage evaporation rate is expected to be somewhere between the PPE and the APE, and closer to APE during the Wet season due to the lower advective energy at this time. On the basis of an assessment against this criterion, Chiew and Wang (1999) concluded that all coefficients except the April and October figures were appropriate and recommended that the Vardavas (1987) values should be used for all months.

Figure 3.3.1 shows the evaporation rates calculated using the Vardavas (1987) pan coefficients and these are compared to the APE and PPE values. All of the Vardavas calculations are in agreement with the seasonal pattern of the APE and the PPE. For February and March, the estimated storage evaporation rates are lower than the APE and Chiew and Wang (1999) concluded that this could be due to errors in the recorded pan evaporation (because of the difficulty in accurately estimating pan evaporation when rainfall is high) or errors in the APE estimates. The overall conclusion was, however, that the best estimates of pond evaporation for Jabiluka would be obtained by using the results of Vardavas (1987).

The difference in annual pond evaporation arising from the use of the full set of Vardavas coefficients compared to that obtained using the coefficients adopted by ERA in the PER for Jabiluka is about 2%. This difference is clearly very small compared to other uncertainties in the modelling of water management and it can be concluded that there is no significant error in evaporation estimates for the Jabiluka water management system arising from the pan coefficients used by ERA in the PER for Jabiluka.

3.3.2 Inverse relationship between evaporation and rainfall

Wasson et al (1998) state that the principal source of error in the evaporation calculations of ERA arises from neglect of the inverse relationship between evaporation and rainfall which arises because solar radiation is lower on cloudy days than on sunny days. They suggest that the adoption of long-term mean values for the pan factors will result in a significant over-estimate of evaporation in very wet months and that this effect could exceed 10% during very wet years.

Chiew and Wang (1999) investigated the significance of the inverse relationship between evaporation and rainfall using data from a number of meteorological stations in the north of the Northern Territory including Jabiru, Maningrida, Middle Point and Darwin. They found that a linear inverse relationship was statistically significant for both the annual data and the quarterly data at each station and that it was most significant at Jabiru. They concluded that this effect should be taken into account in their modelling of the water management system at Jabiluka and they evaluated the significance of the effect on the required pond volume. The conclusion reached was that the retention pond volume would need to be increased by about 3% as a result of both the inverse relationship and interannual variability in evaporation.
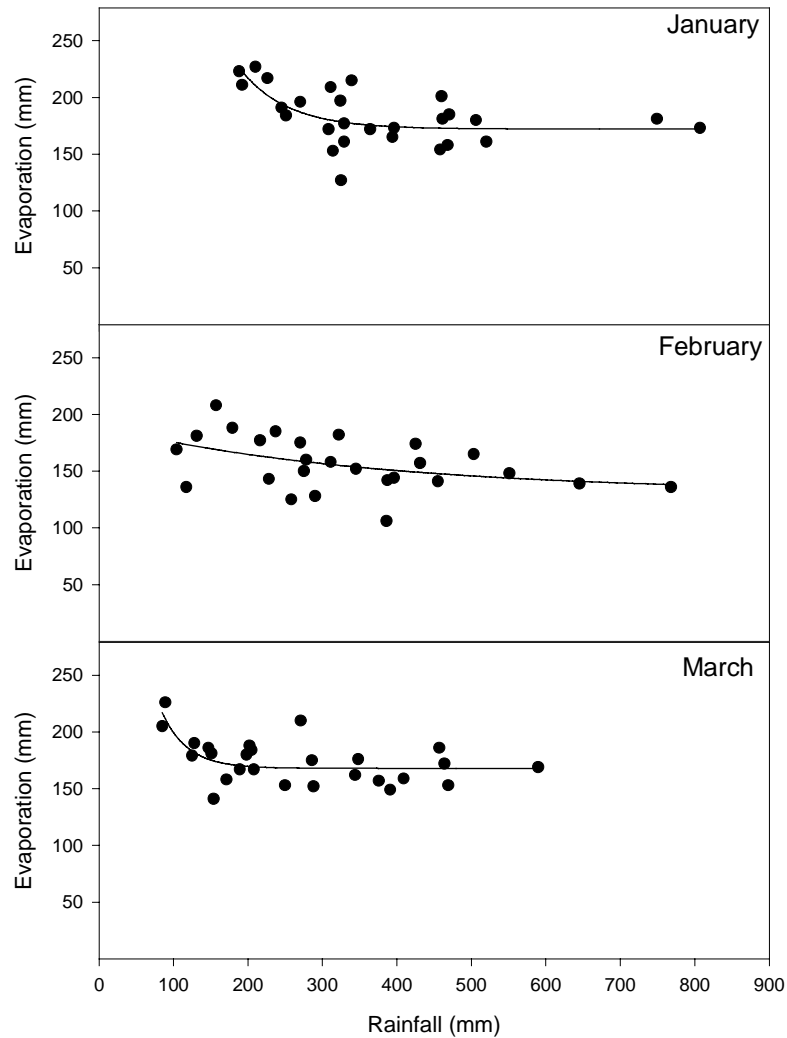
Figure 3.3.2 Relationship between evaporation and rainfall at Jabiru
for the months of January, February and March

There is, however, evidence that even this small effect is an over-estimate because, during the principal months of the Wet season (December to March), cloud cover is often extensive even when there is no rainfall. As a result, the relationship between evaporation and rainfall during any given month will not be linear but evaporation will tend towards a constant lower value at higher rainfall values. This effect is clearly illustrated in figure 3.3.2 where evaporation at Jabiru is plotted against rainfall for the principal Wet season months of January, February and March. The line through the data in each case is of the form

$$E = E_0 + ae^{-bR}$$

where a and b are constants. For January and March, evaporation is essentially constant for values of rainfall above the average for the month while for February a decrease (about 6%) in evaporation is observed between the average rainfall and the maximum in the record. Hence the assumption of a linear relationship between evaporation and rainfall will result in an underestimate of the evaporation in very wet years.

The inverse relationship between evaporation and rainfall could, however, have greater significance in drought years because the use of long-term average monthly values for evaporation will lead to a significant underestimate of evaporation in those years. This may lead to the need to import water from the bore field to maintain plant operation. For this

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reason, it is recommended that a linear relationship between evaporation and rainfall is incorporated in future water management modelling because this will yield conservative results under high rainfall conditions and more realistic results under drought conditions than would be obtained using the long-term monthly average evaporation.

The Supervising Scientist's conclusions on the claims of Wasson et al (1998) on the deficiencies of ERA's estimates of evaporation from open water at the Jabiluka site are:

- All of the suggestions made by Wasson et al (1998) to check the validity of the evaporation pan factors used by ERA had already been taken into account in the evaporation calculations presented by ERA in its hydrological modelling of the water management system for the Jabiluka project.

- Based upon two recent independent reviews, it is recommended that, in all future hydrological modelling of the Jabiluka water management system, the pan factors proposed by the Supervising Scientist in 1987 be used.

- The difference in annual pond evaporation arising from the use of the pan factors recommended by the Supervising Scientist compared to that obtained using the factors adopted by ERA in the PER for Jabiluka is small (about 2%). This difference is well within current expectations of the accuracy of water management modelling.

- The volume of the retention pond at Jabiluka would need to be increased by about 3% to take into account the inter-annual variation in evaporation and the inverse relationship relationship between evaporation and rainfall.

- This estimate is, however, considered to be an overestimate because the relationship between evaporation and rainfall is not linear. Rather, evaporation during the main months of the Wet season tends towards a constant value at high rainfall values.

- It is recommended that a linear relationship between evaporation and rainfall is incorporated in future water management modelling because this will yield conservative results under high rainfall conditions and more realistic results under drought conditions than would be obtained using the long-term monthly average evaporation.

3.4 Evaporation in the mine

In both the Environmental Impact Statement and the Public Environment Report, ERA proposed the use of enhanced evaporation in the exit stream of the ventilation system to remove water from the Total Containment Zone at the Jabiluka mine. Air passing through the underground workings and stopes will evaporate free water which will subsequently be discharged via the ventilation exhaust system. The company plans to maximise this form of enhanced evaporation in years in which there is surplus water in the system by transferring excess water from the TCZ water storage pond for subsequent evaporation in the ventilation system. Disposal of this excess water would be by the use of sprays or misting devices near the exhaust ventilation vents with monitors to maintain humidity of the exhaust air below 85% (or any other designated safe level) to avoid the emission of droplets from the vents.

The calculations presented by ERA in the EIS and the PER show that disposal of 40,000 m^3 per annum should be possible in the ventilation shafts, with this value increasing to a total of 90,000 m^3 when evaporation from all underground sources is taken into account. For the Jabiluka Mill Alternative (original proposal) in extremely wet years, this figure represents about 20% of the total losses in the water balance model (table B.1.8 in Appendix B of the PER). This percentage will not be greater in a system that meets the requirements of the

Commonwealth Government (in which all tailings will be returned underground) because evaporation from the tailings ponds was not included in the water balance modelling presented in the PER.

The submission of Wasson et al (1998) states (page 13) that a major error exists in the calculations presented in the EIS and the PER for the quantity of water that can be evaporated in the ventilation shafts. They point out that the latent energy of evaporation has to be taken from the air stream resulting in a drop in the air temperature; this, in turn, will reduce the capacity of the air to hold moisture.

The basic physics underlying these statements is not disputed by the Supervising Scientist but the conclusion that a major error is present in the calculations is not supported.

As stated in Appendix J of the draft EIS, the absolute humidity or water vapour density, p, may be calculated from the ideal gas law which, when the vapour pressure, Pv, is given in kPa, reduces to

$$p = 2.167 Pv / T \qquad (1)$$

where p is in kg/m^3 and T is in ^{o}K. Figure 3.4.1 (upper graph) shows the dependence of vapour pressure on temperature at an atmospheric pressure of 100 kPa; the data were taken from Kaye and Laby (1978, p 173). From these data the absolute humidity values have been calculated using equation (1); they are presented in figure 3.4.1 (lower graph).

For T=30 ^{o}C, the values of p for 85% and 60% relative humidity are 0.0259 kg/m^3 and 0.0182 kg/m^3 respectively. If no external energy is provided, the latent heat of vaporisation for the difference, 0.0077 kg/m^3 would need to be provided by the air stream. This would result in a drop in temperature, ΔT, given by

$$\Delta T = L\Delta p / \rho C_P \qquad (2)$$

where Δp is the change in humidity, L is the latent heat of vaporisation, ρ is the density of air and C_p is the specific heat of air. Using $L = 2.43 \ 10^6$ J/kg (Kaye & Laby 1978, p 235), $\rho = 1.149$ kg/m^3 (Kaye & Laby 1978, p 18) and $C_p = 1010$ J/kg/^{o}C (CRC 1995, p 6-1), the decrease in temperature resulting from the vaporisation of the water would be 16°C. As can be seen from figure 3.4.1, the absolute humidity (ie fully saturated) at 14°C is about 0.012 kg/m^3, a figure considerably less than the initial vapour density. Hence, the target evaporation figure cannot be achieved.

The optimum performance of the proposed system can be derived as follows. As water is added to the air stream and evaporated, the water vapour density will increase linearly with decreasing temperature until a temperature is reached at which the air stream is saturated. The gradient of this linear relationship is given by

$$dp / dT = -\rho C_P / L = -4.78 \ 10^{-4} (kg / m^3) /^o C \qquad (3)$$

Hence,

$$p = p_0 - (\rho C_p / L)(T - T_0) \qquad (4)$$

For 60% relative humidity, $p_0 = 0.0182$(kg/m^3) at $T_0 = 30$^{o}C. This line is shown in figure 3.4.1. It intercepts the graph of absolute humidity at about 23.6^{o}C which, as proposed by Wasson et al (1998), is the wet bulb temperature (estimated as 23.8^{o}C from the data in CRC (1995) p15−22). At this temperature the absolute humidity is 0.0213 (kg/m^3). Thus the maximum quantity of water that can be evaporated is

$$p = 0.0213 - 0.0182 = 0.0031(kg/m^3).$$

This value is about 40% of the design value presented in Appendix J of the draft EIS.
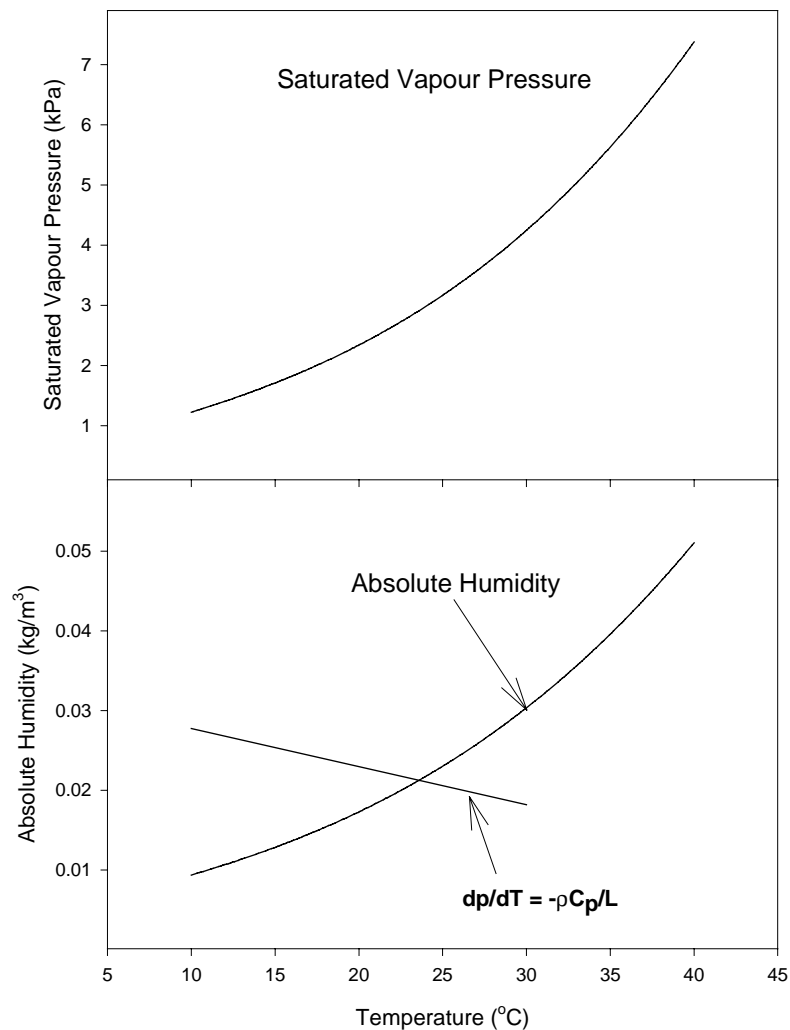
Figure 3.4.1 Variation of saturated vapour pressure (upper graph) and absolute humidity (lower graph) with temperature at atmospheric pressure P=100kPa

These observations, however, do not imply that a major error exists in the proposal put forward for water management at the Jabiluka mine. If the latent heat of evaporation were to be supplied (for example, by standard humidifiers) there would be no need to take the above drop in temperature into account and the volume of water that could be evaporated would remain that estimated in the EIS and the PER. The Supervising Scientist consulted the engineer who advised ERA on this issue (Mr Douglas Rudd, Kinhill Pty Ltd) who advised that the calculations were provided to indicate the capacity of the ventilation system to dispose of additional water through evaporation. It was recognised that energy input via heaters, hot air blowers or staged misting/humidifiers would be required to achieve the full indicated disposal volume. These issues were, however, matters to be dealt with at the detailed design stage of the project when the potential of this method of water disposal could be evaluated (ie a cost benefit analysis) in a comparison with other methods such as increasing the area of the retention pond.

However, the power consumption of such a system could be considerable. The power consumption of a humidifier designed to provide the latent heat of evaporation will be determined by the operating conditions in the Dry season when the maximum evaporative capacity exists. To estimate the power required, the data presented in table J.2 of Appendix J of the draft EIS have been used.

For the period August to November, the total evaporation rate is $R = 35$ m³/h. Hence the power required (assuming 100% efficiency) is

$$W = R(m^3/s)L(J/kg)\rho(kg/m^3) = 24MW$$

The capital cost and the operating costs for the humidifier will, therefore, be considerable. In addition the relative environmental advantages and disadvantages associated with the establishment of the required generator capacity at Jabiluka would need to be assessed. The latter would need to be compared to the alternative option of increasing the area of the retention pond.

The area of the retention pond would need to rise from 9 ha to approximately 13 ha to provide the required evaporative capacity if no evaporation occurs in the ventilation shafts. This area is small compared to the total area of retention and tailings ponds proposed in the original JMA proposal and is only 2% of the disturbed area at the nearby Ranger mine. The environmental impact arising from such an increase, should it need to be part of the project, is, therefore, not considered to be significant.

In summary,

- The observation by Wasson et al (1998) that the latent heat of evaporation needs to be supplied is correct. The conclusion that this results in a major error is, however, invalid because the energy required can be supplied externally, and it was the intention of the design engineer that the optimum way of doing this would be assessed at the detailed design stage once approval for the project to proceed had been given.

- The capital and operating costs of a humidifier system designed to meet the evaporation energy needs would be high and a cost benefit analysis of various water management options will be required before a final decision on the installation of a humidifier system is made.

- If it is decided that the cost of installing and running a humidifier system is too high or that the environmental impact is unacceptable, the retention pond at Jabiluka would need to be increased in area from 9 ha to about 13 ha. Given the experience of the Ranger Mine, which has a disturbed area of about 500 ha, this 4 ha increase is not expected to give rise to any detectable environmental impact.

3.5 Summary of findings on hydrological modelling issues

The conclusions and recommendations of the Supervising Scientist on the hydrological modelling issues raised by Wasson et al (1998) are as follows.

Estimate of the 1:10,000 AEP annual rainfall
- It is recommended that the Oenpelli rainfall record for the years 1917 to 1998 should be used for estimating the 1:10,000 AEP annual rainfall and for other hydrological modelling for the Jabiluka project because it is much more extensive than that at Jabiru and is consistent with the Jabiru record in the period of overlap.

- The recommended value for the 1:10,000 AEP annual rainfall is 2460 mm with 95% confidence limits of ±190 mm. This estimate is in very good agreement with the value adopted by ERA, 2450 mm.

- It is acknowledged that there may be some residual model dependence in the recommended value for the 1:10,000 AEP annual rainfall. However, this is not important for modelling of the Jabiluka water management system in this review because a Monte Carlo simulation method is used based upon stochastically generated rainfall data.

Evaporation from open water

- All of the suggestions made by Wasson et al (1998) to check the validity of the evaporation pan factors used by ERA had already been taken into account in the evaporation calculations presented by ERA in its hydrological modelling of the water management system for the Jabiluka project.

- Based upon two recent independent reviews, it is recommended that, in all future hydrological modelling of the Jabiluka water management system, the pan factors proposed by the Supervising Scientist in 1987 be used.

- The difference in annual pond evaporation arising from the use of the pan factors recommended by the Supervising Scientist compared to that obtained using the factors adopted by ERA in the PER for Jabiluka is small (about 2%). This difference is well within current expectations of the accuracy of water management modelling.

- The volume of the retention pond at Jabiluka would need to be increased by about 3% to take into account the inter-annual variation in evaporation and the inverse relationship relationship between evaporation and rainfall.

- This estimate is, however, considered to be an overestimate because the relationship between evaporation and rainfall is not linear. Rather, evaporation during the main months of the Wet season tends towards a constant value at high rainfall values.

- It is recommended that a linear relationship between evaporation and rainfall is incorporated in future water management modelling because this will yield conservative results under high rainfall conditions and more realistic results under drought conditions than would be obtained using the long-term monthly average evaporation.

Evaporation in the mine ventilation shafts

- The observation by Wasson et al (1998) that the latent heat of evaporation needs to be supplied is correct. The conclusion that this results in a major error is, however, invalid because the energy required can be supplied externally, and it was the intention of the design engineer that the optimum way of doing this would be assessed at the detailed design stage once approval for the project to proceed had been given.

- The capital and operating costs of a humidifier system designed to meet the evaporation energy needs would be high and a cost benefit analysis of various water management options will be required before a final decision on the installation of a humidifier system is made.

- If it is decided that the cost of installing and running a humidifier system is too high or that the environmental impact is unacceptable, the retention pond at Jabiluka would need to be increased in area from 9 ha to about 13 ha. Given the experience of the Ranger Mine, which has a disturbed area of about 500 ha, this 4 ha increase is not expected to give rise to any detectable environmental impact.

4 Prediction and impact of severe weather events

4.1 Introduction

The previous chapter of this report addressed hydrological modelling issues under current climatic conditions. It included, however, an assessment of 'severe weather events' in the sense of severe annual rainfall events that would only be expected to occur once in 10,000 years. The submission of Wasson et al to the Mission of the World Heritage Committee (Wasson et al 1998) addressed a number of other types of 'severe weather events' such as:

- evidence in the historical record of very severe weather events,

- the appropriateness of estimates of Probable Maximum Precipitation events (PMP), and

- the effect of climate change on the design of water management systems.

These issues are addressed in this chapter.

4.2 Evidence on past severe weather events in the region

In their submission to the Mission of the World Heritage Committee, Wasson et al (1998) presented evidence that, in the past, climatic conditions in the region have been very different to current conditions. They refer to the work of Wasson et al (1992) in which it was shown that a transition from a much drier climate took place somewhere between 1900 and 1400 years before present. They also refer to the work of Nott (1996) which demonstrated that river discharges in Waterfall Creek in the south of Kakadu National Park were about five times larger than current discharges between 8000 and 4000 years before present. On the basis of this evidence, Wasson et al (1998) conclude that *'the design of bunds, and all other structures to contain tailings, water and other wastes, at both Jabiluka and Ranger, is based on principles that are grossly inadequate. We simply do not know if the design structures can withstand the major rainfall events of the future, so the integrity of Kakadu NP cannot be guaranteed with any probability'*.

The Supervising Scientist does not dispute the evidence cited by Wasson et al (1998) from the work of Nott (1996) and Wasson et al (1992) that the climate of the region has been significantly different from the present climate during the past 10,000 years nor the conclusion that similar differences in climate may occur during the next 10,000 years. What is disputed, however, is the application of this scientific evidence to the management of water and tailings at Jabiluka. The criticisms of Wasson et al (1998) are all premised on the *assumed* need to design and build tailings and water retention dams that will be structurally stable for 10,000 years and will totally contain all water that might accumulate over this period. This assumption is totally incorrect and reflects a lack of understanding of the accepted proposal for milling at Jabiluka by the authors of the submission.

The storage of tailings or contaminated water on the land surface over a period of 10,000 years is not an issue. The project approved by the Minister for the Environment required all tailings to be returned underground to the mine void and to additional stopes or silos specially excavated to contain the tailings. There will, therefore, be no need to contain tailings in surface repositories for any period longer than the mine life, approximately 30 years.

Wasson et al (1998) also propose that if the water retention ponds become seriously contaminated, then they too will need to be stable for 10,000 years. This is not the case.

Following completion of mining, all water in the water retention ponds will evaporate over a period of a few years. This will be possible because, on an annual average basis, true pond evaporation exceeds rainfall by about 500 mm per annum. Once the ponds have been evaporated to dryness, all contaminated sediment in the ponds will be collected and placed underground with the tailings. The pond structures will then be rehabilitated. There will be no water retention ponds following rehabilitation.

For these reasons, the strongly worded criticism in Wasson et al (1998) that the proponent has assumed stationarity of climate over a period of 10,000 years is quite without foundation.

4.3 Probable maximum precipitation events

The submission of Wasson et al (1998) notes that the criteria for design of bunds to prevent water from catchments adjacent to the TCZ entering the containment zone are conservative. These included the adoption of runoff coefficients of one and adoption of the 6-minute PMP as the design storm intensity. Similar positive comments were made about the design criteria to prevent water within the TCZ overtopping the containment bunds. They note, however, that PMPs over a 10,000 year period would probably be much greater. This issue has been addressed in the previous section where it was concluded that a 10,000 year period is not relevant to the design of surface structures.

ERA gives a value for the 6-minute PMP in the Draft EIS but does not explain its origin. For this reason, the Supervising Scientist requested that a review of PMPs for the region be conducted by the Bureau of Meteorology. The results of this review are given in Bureau of Meteorology (1999).

Point value PMPs for durations from 15 minutes (the minimum value normally calculated) to six hours were calculated for Jabiluka using the Generalised Short Duration Method (GSDM, Bureau of Meteorology 1994). Then, each PMP (depth in mm) was converted to intensity (mm/hr) and plotted against duration using linear scales. The best-fit to this intensity vs duration curve was a power law ($R^2 = 0.99$). The curve was extrapolated back to obtain an estimate of the 6-minute intensity of 1380 mm/hr.

A second approach adopted was based on the Intensity-Frequency-Duration (IFD) ratio. IFD information was produced for the nearest grid point to Jabiluka. For 100 year IFD, the ratio of the 6-minute to the 15-minute intensities was calculated. The 15-minute PMP intensity was then multiplied by this ratio to obtain an estimate of the 6-minute PMP of 1320 mm/hr.

These two estimates of the 6-minute PMP differ by less than 4%, leading to some confidence in the estimate. In the interests of conservatism, the larger value of 1380 mm/hr is recommended. The 6-minute PMP intensity estimate adopted by ERA (Draft EIS, Appendix J, page J3) for the Jabiluka project is 1150 mm/hr, approximately 20% lower than the value recommended by the Bureau of Meteorology. It is recommended that the Bureau value be used in the detailed design of the Jabiluka project.

A full set of PMP values appropriate for Jabiluka is provided by the Bureau of Meteorology (1999). The effect of climate change over the next 30 years is discussed in the next section.

4.4 Effect of climate change on hydrological modelling

It was concluded in section 4.2 that the effects of climate change over the next 10,000 years need not be considered in the design of the surface water storage facilities at Jabiluka. However, what is required is that possible or likely variations in climate over the next 30 years are properly taken into account in the design of the water management system.

This requirement was pointed out by the Supervising Scientist in his comments on the Draft EIS. ERA responded (Supplement to the Draft EIS, p5–27) that *'Current indications of climate change are that the margins of change are less than the order of accuracy of calculations. The adoption of extreme events used for water balance calculation will more than accommodate any fluctuations that may be associated with any greenhouse influences over the 28 years of mine operation'.*

The assessment that greenhouse associated effects are likely to be small over the next 30 years was considered valid (see further discussion below) but the Supervising Scientist was also conscious of the need to take into account non-greenhouse effects such as periodic changes in the mean annual rainfall that occur in the past meteorological record. These had been identified previously by the Supervising Scientist (Carter 1990).

The decision of the Minister for the Environment on the Jabiluka Mill Alternative required the proponent, ERA, to prepare an amended proposal to the satisfaction of the Supervising Scientist under which all tailings would be stored underground. The issue of climate change over the next 30 years is an issue that would have been addressed when assessing the detailed design proposed by ERA. Given the concerns expressed by the World Heritage Committee, the assessment of climate change effects has been brought forward and has been carried out by the Supervising Scientist as part of this review rather than being commissioned by ERA as part of its detailed design study.

4.4.1 Review of existing information on climate change

The CSIRO Division of Atmospheric Research carried out a three year study (1994–1997) on 'Climate change under enhanced greenhouse conditions in northern Australia' under a consultancy with the governments of the Northern Territory, Western Australia and Queensland. The final report on the project (CSIRO 1998) was published in January 1998.

The results obtained in this project were inconclusive on the issue of expected changes over the next 30 years in mean rainfall in the region. All models used in the project broadly agreed that there would be a decrease in Dry season rainfall. However, global climate models (GCM) with simplified oceans (Slab models) indicated a likely increase in Wet season rainfall (in the range 2–12 per cent) by 2030, whereas coupled ocean models show a decrease (0–8 per cent) by 2030 for Wet season rainfall. Since most of the rainfall occurs in the Wet season, this disparity is important.

In Slab models, a simplified ocean component is used, usually consisting of a well-mixed 50 m layer and climate changes are simulated for a changed equilibrium state. That is, the climate is assumed to have settled down following stabilisation of greenhouse gas emissions, a situation that will not occur for the foreseeable future. Slab models are, therefore, not expected to be reliable for transition conditions over the next 30 years.

Coupled ocean models, on the other hand, have a full ocean model that is coupled to the atmosphere. They are dynamic models that can directly simulate transient climate conditions and are expected to be more reliable in their predictions for the next 30 years.

An important issue in making climate change predictions for specific regions is that the GCMs, both Slab and coupled ocean models, have coarse resolution (grid point spacing typically 300–500 km). To obtain more detailed and realistic predictions for expected changes in rainfall at the regional level, it is necessary to nest regional climate models (such as the CSIRO model DARLAM) into the global climate models. At the time of publication of the report on climate change in northern Australia (CSIRO 1998), DARLAM had only been

incorporated in Slab models, not in the more realistic coupled ocean models. The report identified this as the next step required for climate change modelling in northern Australia.

Thus, the response by ERA that greenhouse induced changes were not expected to be significant for hydrological modelling over the next 30 years has some justification because all of the coupled ocean models, which are considered to be more realistic, predicted a reduction in Wet season rainfall. However, until regional climate models are incorporated into the global climate models, this conclusion should be considered preliminary.
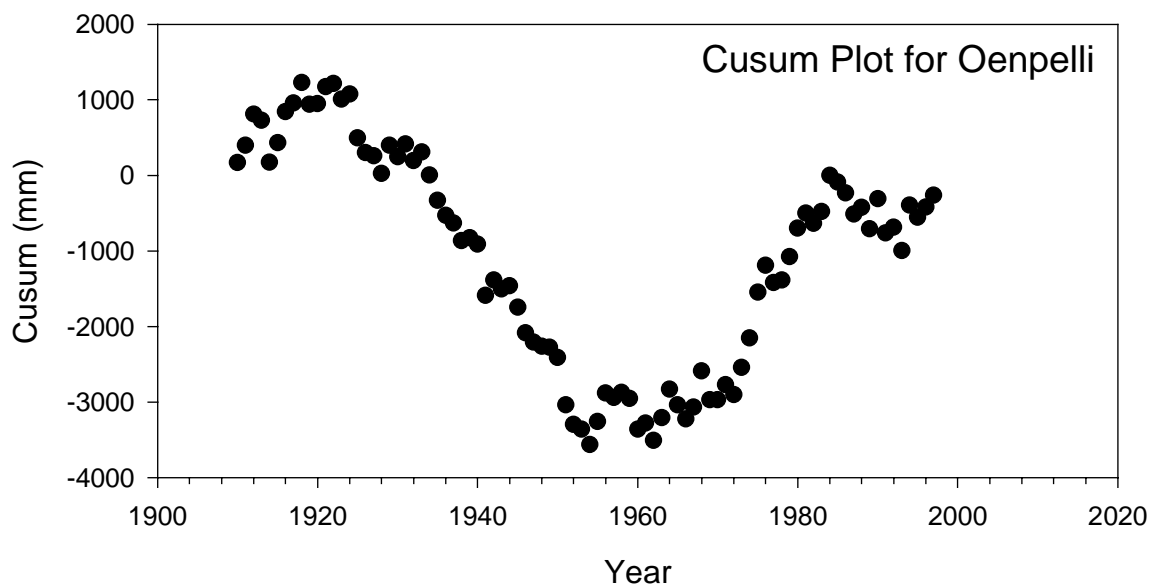
Figure 4.4.1 Cusum plot for the annual rainfall records at Oenpelli showing low average rainfall from 1932–1952 and high average rainfall from 1970–1984

The above discussion refers only to greenhouse induced change in climate and does not include decadal-scale change due to natural climatic variability. Indeed, the methods used in analysing past data to test for greenhouse induced change involve the specific removal of decadal-scale trends from the record. In this case, decadal-scale change must be separately examined (Jones at al 1999).

It was noted in section 3.2.1 above that the Supervising Scientist (Carter 1990) used a *cusum* technique to examine long-term cycles or trends in the mean annual rainfall at a number of meteorological stations in the Northern Territory using rainfall records up to 1988. This analysis revealed that the period between the mid-1960s until the mid-1980s was one of significantly higher average rainfall than the long term mean. This conclusion was valid for the stations at Darwin, Oenpelli, Pine Creek and Katherine.

The *cusum* analysis for the Oenpelli data set, including rainfall records from 1991–1998, is shown in figure 4.4.1. It can be shown (eg Mittag & Rinne 1993) that the gradient of the *cusum* graph at time *t* is the difference between the mean at that time and the long-term mean. The data in figure 4.4.1, therefore, show that, at Oenpelli, there have been two extended periods in the past 87 years during which the mean annual rainfall for the period has been significantly different from the long-term mean annual rainfall. From 1932–1952, the mean rainfall was about 1220 mm, lower than the long-term mean by about 13%. From 1970–1984 the mean rainfall was about 1600 mm, higher than the long-term mean by about 15%. It is clear that such decadal-scale variation in mean rainfall could have a significant impact on

hydrological modelling for the Jabiluka mine site and needs to be taken into account in the design of the water management system.

The Supervising Scientist commissioned the CSIRO Division of Atmospheric Research to examine both greenhouse induced change and decadal-scale change as part of this review (Jones et al 1999, Attachment C). The results are presented in subsequent sections.

4.4.2 Climate change analysis for Jabiluka

CSIRO Atmospheric Research currently simulates climate change using the CSIRO Mark 2 coupled Global Climate Model and the DARLAM Regional Climate Model. In the current review, three experiments were analysed by Jones et al (1999) using these models. In two experiments, the CSIRO coupled ocean-atmosphere model was integrated from 1881 to 2100 with a gradually increasing CO_2 concentration equivalent to the forcing produced by all greenhouse gases in the mid case IS92a emission scenario (IPCC 1996). (Definitions of terms used are given in Jones et al (1999).) One simulation also incorporates the direct effects of atmospheric sulphate aerosol (the indirect effects, or atmospheric feedbacks, are omitted) which has a cooling effect. The regional climate model, DARLAM, with a finer spatial resolution of 125 km, was nested in the CSIRO Mark 2 greenhouse-gas-only simulation in order to provide higher resolution data. Results from three GCMs from other modelling groups obtained from the IPCC Data Distribution Centre have also been used in the analysis. The models are summarised in table 4.4.1.

Table 4.4.1 Model runs used to produce the regional scenarios presented in this report

Centre	Model	Emission Scenario	Features	Years
CSIRO, Australia[1]	Mk2	IS92a equivalent CO_2	No sulphates, GM ocean	1881–2100
CSIRO, Australia	Mk2 with sulphates	IS92a equivalent CO_2	Sulphates, GM ocean	1881–2100
CSIRO, Australia[2]	DARLAM 125 km	IS92a equivalent CO_2	Nested in CSIRO Mk2	1961–2100
DKRZ, Germany[3]	ECHAM4/OPYC3	IS92a	No sulphates	1860–2099
Hadley Centre, UK[4]	HADCM2	1% CO_2 pa	No sulphates	1861–2100
Canadian CCMA[5]	CGCM1	1% CO_2 pa	No sulphates	1900–2100

[1]Gordon & O'Farrell (1996), [2]McGregor & Katzfey (1998), [3]DKRZ-Model User Support Group (1992), Oberhuber (1992), [4]Cullen (1993), [5]Flato et al (submitted)

Mean temperature increase at Jabiluka

Global warming projections from the IPCC (1996) incorporate uncertainties in greenhouse gas emission rates and climate sensitivity. The contributing emission rates are applied through the IS92a–f emission scenarios. These scenarios incorporate the major greenhouse gases, including CO_2, CH_4, N_2O and halogenated compounds, and sulphate aerosols which lead to cooling. Global warming projections also incorporate uncertainties due to climate sensitivity, ranging from 1.5–4.5ºC at $2\times CO_2$. The resulting range of projected global warming for 2030 is 0.4–0.8ºC (IPCC 1996).

The models reproduce patterns of regional temperature reasonably well when grid box resolution is taken into account. The pattern of warming in each model shows greater changes inland than on the coast because the land heats faster than the ocean. This creates a gradient of warming from the ocean which usually warms less than the rate of global warming and the land which warms faster. To create a standard comparison for each model, temperature change per degree of global warming was regridded from the original model grid network and averaged over a $2\times2º$ box, with the coordinates of 11.5–13.5ºS and 132–134ºE, centred over Jabiluka. These results reflect the buffering effect of the Arafura Sea on

projected temperature in the Jabiluka Region, limiting local warming at, or just below, the level of global warming. They are presented in table 4.4.2

Table 4.4.2 Temperature change per degree global of warming from six climate models averaged over the Jabiluka region (11.5–13.5°S and 132–134°E) on an annual basis

Change per degree of global warming	DARLAM 125	CSIRO Mark2 (GHG only)	CSIRO Mark2 (sulphates)	DKRZ	Hadley Centre	Canadian CCMA
Annual average	0.86	0.89	0.92	1.01	0.93	1.00

Using the projected global warming of 0.4–0.8°C by 2030, the projected temperature increase in the region of Jabiluka is in the range 0.35–0.8 (rounded to the nearest 0.05°C) from the results in table 4.4.2.

Greenhouse induced change in mean annual rainfall

The output of each Global Climate Model listed in table 4.4.1 has been analysed by Jones et al (1999) to create regional projections of mean annual rainfall in the region over the next 30 years. The results for the Wet and Dry seasons are presented in table 4.4.3. Detailed projections on a monthly basis are given in Jones at al (1999).

As shown in table 4.4.3, the largest increase in the monsoon season, November to April, is 1% per degree of global warming, with decreases of up to 8%. The Dry season produced much more variable results ranging from an increase of 8% to a decrease of over 60%. These changes are less important for annual rainfall than those for the Wet season, due to the relatively low average rainfall that occurs during the Dry season.

Using the projected global temperature change in 2030, 0.4–0.8°C, these data indicate a range of change for the Wet season rainfall of +1% to -6% by 2030. Thus, the latest modelling, which includes the nesting of a regional climate model into the ocean coupled global climate model, confirms the expectation that any increase in Wet season average rainfall due to greenhouse warming is likely to be small (1%).

The confidence invested in this range consists of the confidence in the range of global warming and the ability of the GCMs to simulate the Australian monsoon. The confidence in the range of global warming is high while for rainfall in the Australian monsoon it is low. Although there are regions where the direction of possible rainfall change can be assessed as fairly robust (the central eastern Pacific Ocean), the results for northern Australia show no such consistency.

Table 4.4.3 Percentage change per degree global warming from six climate models averaged over 11–15°S and 130.5–135.5°E for each month and the half-yearly periods, May to October and November to April

Period	DARLAM 125	CSIRO Mark2 (GHG only)	CSIRO Mark2 (sulphates)	DKRZ	Hadley Centre	Canadian CCMA
May to Oct	8	5	4	-63	-15	-4
Nov to Apr	1	1	1	-3	-8	0

Long-term trends on mean annual rainfall

Jones et al (1999) analysed the Oenpelli rainfall record to determine historical rainfall trends and rainfall variability. The results are presented in figure 4.4.2. Significant decadal-scale

variability is demonstrated by the 10-year moving average and a trend of 1.7 mm pa that is not statistically significant.
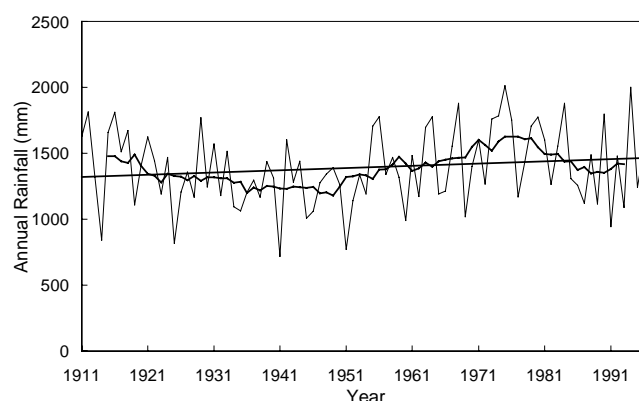
Figure 4.4.2 Average annual rainfall from Oenpelli 1911–1997, showing a
10-year moving average and linear trend of 1.7 mm pa

One of the issues posed by climate change when considering a historical record is one of non-stationarity, eg that the mean is not fixed over the life of a time series. This may already be the case with global temperatures, although the debate as to whether global temperature has exceeded the rate of natural variability is still continuing. With the Oenpelli rainfall record, there is a historical trend, but it is statistically non-significant and lies well within historical variability. However, by assuming the persistence of this trend and imposing the historical rate of trend of 1.7 mm pa for 30 years (ie from 2000 to 2030) there is an increase of 4% over the historical mean. As the persistence of historical trends is very possible (with or without a component of climate change), an increase of 4% in annual rainfall by 2030 is assumed to be a plausible scenario. This is discussed further below.

Decadal scale variation in the mean rainfall
The effect of decadal variability was assessed by detrending the series (ie removal of the 1.7 mm per annum trend) and standardising the 10 year running mean. Its highest and lowest points as a proportion of the mean were ±15% over the historical period, so this was chosen as the limit of decadal variability. This result is, as expected, similar to that derived from the *cusum* approach outlined in section 4.4.1.

While the decadal scale variation in the mean rainfall is significant and needs to be properly taken into account in design of the water management system, its presence in the historical record implies that, to some extent at least, it is contributing to the mean and the standard deviation of the long-term record. It is, therefore, inherent in the prediction of extreme events derived from that record, for example the 1:10,000 AEP rainfall, and it will also be contributing to the distribution used to generate stochastic rainfall series (see next chapter) in the modelling of the Jabiluka water management system. The extent to which the decadal-scale variation is taken into account in these stochastically generated rainfall series needs to be assessed before considering the incorporation of decadal-scale variation as a component of climate change.
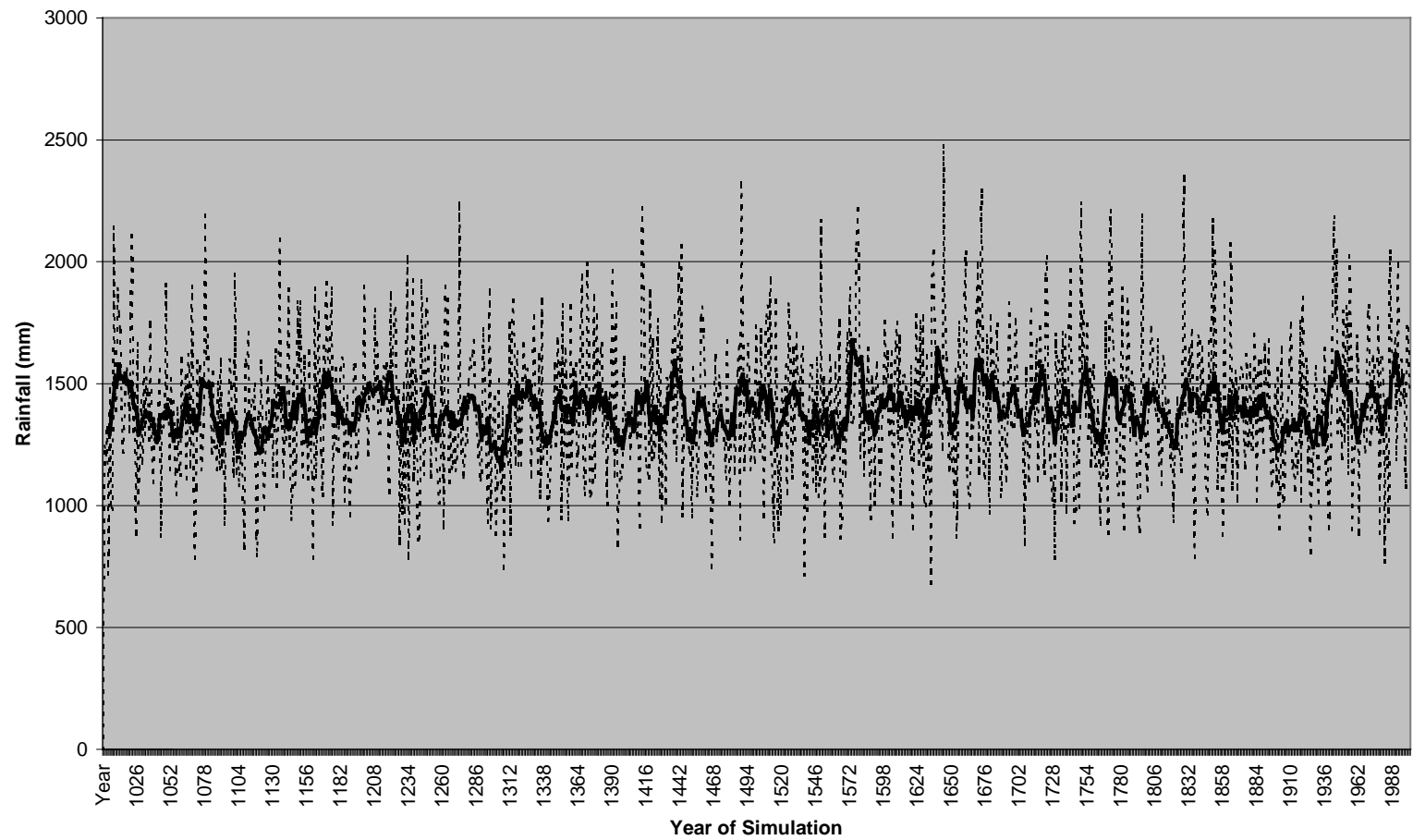
Figure 4.4.3 Examination of 1000 years of simulated rainfall data to determine the extent to which decadal scale variation is present

Jones et al (1999) analysed a 1000 year sequence of annual rainfall data stochastically generated by Chiew and Wang (1999) using the procedures described in section 5.2.2 and compared the statistics of decadal scale variation observed in the generated data with those observed in the rainfall record for Oenpelli. The 1000 year period of generated data is shown in figure 4.4.3; also plotted is the ten year running mean. It is clear that the simulated data do contain extensive periods of both higher-than-average and lower-than-average rainfall.

A shorter sample of that artificial record with the same length as the historical series was analysed. It shows decadal-scale variability of a similar magnitude to that of the historical series but without the same regularity. The coefficient of variability of the 10-year moving average for the shorter record from the 1000-year sample is 6.0±4.2% while for the historical series it is 6.5±4.1%. It can be concluded, therefore, that decadal scale variability has been fully accounted for in the hydrological modelling of the Jabiluka water management system presented in section 5.2.3 and there is no justification for adding such a component into a climate change scenario.

The long-term average of the sample also exhibited a trend upwards of 1 mm pa, similar to the historical series at 1.7 mm pa, but the record contains three simulated rainfall totals that exceed the historical maximum of 2012 mm in the 1975–1976 Wet season. This may be due to the positively skewed distribution of annual rainfall in the sample of the artificial series generated and analysed by Chiew and Wang (1999). Therefore, a 3% increase in average rainfall over the next 30 years is likely to be contained within the trends already sampled and applied in the hydrological modelling of Chiew and Wang (1999). Jones et al (1999) concluded that further hydrological modelling incorporating an additional 3% increase in the mean annual rainfall would only be justified if evidence from new climate simulations showed that greater rainfall increases were likely.

Effect of climate change on storm intensity

The effect of climate change on extreme daily rainfall intensity and on PMPs was also investigated by Jones et al (1999). As in previous studies, it was found that the intensity of extreme events is likely to increase despite the fact that there is an overall decrease in the annual rainfall. In the Wet season, average rainfall was found to decrease by 4.5% but the intensity and frequency of extreme rainfall increases. For example, the intensity of the 1-in-10 year event increases by 4%, or the present 10-year event becomes a 9-year event by 2030. The decrease in average rainfall requires a reduction in the frequency or intensity of moderate events. There is a hint of this in the tendency for smaller increases in the strength of events with smaller return periods (and probable decreases in the strength of events with return periods of less than 1 year). Hence the largest summer storms become larger, and moderate downpours become weaker.

An assessment of the significance of these findings on the intensity of storms for the design of water containment ponds at Jabiluka is required. This will be considered in Chapter 5.

The modelling of Jones et al 1999 also suggests that there could be a significant increase in the magnitude of PMP events, with increases of up to 30% being suggested. Possible increases of this magnitude should be taken into account in the final design of the Jabiluka water management system by increasing the height of exclusion bunds.

4.5 Summary of findings on severe weather events

Evidence on past severe weather events in the region

- The assumption of Wasson et al (1998) on need to design and build tailings and water retention dams that will be structurally stable for 10,000 years and will totally contain all water that might accumulate over this period is incorrect.

- The project approved by the Minister for the Environment required all tailings to be returned underground to the mine void and to additional stopes or silos specially excavated to contain the tailings. There will, therefore, be no need to contain tailings in surface repositories for any period longer than the mine life, approximately 30 years. Similarly, water retention structures will be evaporated to dryness and rehabilitated at the cessation of mining.

- The strongly worded criticism in Wasson et al (1998) that the proponent has assumed stationarity of climate over a period of 10,000 years is, therefore, without foundation. Citing this and information on significantly different climate regimes in the region in the past few thousand years as evidence that 'the integrity of Kakadu cannot be guaranteed with any probability' is unjustified.

Probable maximum precipitation events

- The 6-minute PMP intensity estimate adopted by ERA for the Jabiluka project is approximately 20% lower than the value recommended by the Bureau of Meteorology. It is recommended that the Bureau value be used in the detailed design of the Jabiluka project.

- A full set of PMP values appropriate for Jabiluka is provided in this report. It is recommended that these values be used, where appropriate, in the detailed design of the Jabiluka project.

Effect of climate change on hydrological modelling

- As recommended previously by the Supervising Scientist, it is important that possible or likely variations in climate over the next 30 years are properly taken into account in the detailed design of the water management system at Jabiluka. This should include non-greenhouse effects such as periodic changes in the mean annual rainfall that occur in the past meteorological record.

- There is substantial agreement in the predictions of the various climate change models on the projected temperature increase in the region of Jabiluka by the year 2030. The increase is expected to be in the range 0.35–0.8ºC.

- There is substantial agreement in the predictions of the various climate change models, including models that incorporate regional climate modelling, on the likely change in the Wet season rainfall in the region of Jabiluka. The predictions range from +1% to -6% by 2030. These models confirm previous expectations that any increase in Wet season average rainfall due to global warming is likely to be small (1%).

- Decadal scale variation is the most significant climate change effect for hydrological modelling of the Jabiluka project. The present review confirms the earlier analysis of the Supervising Scientist that this effect could be as large as 15% over the next 30 years. However, this review has established that stochastic rainfall series modelling, based upon the Oenpelli rainfall record, fully accounts for decadal scale variability and that there is no need to include this effect explicitly in a climate change scenario.

- Analysis of the historical rainfall record at Oenpelli reveals an upward trend of 1.7 mm per annum in the mean annual rainfall that may be attributed to global warming and which should be added to the model predictions. The observed trend is not statistically significant but the adoption of a precautionary approach implies that the significance of this possible trend should be assessed in hydrological modelling of the Jabiluka project. However, stochastic rainfall series modelling, based upon the Oenpelli rainfall record, also exhibits a similar trend and it is concluded that there is no need to include this effect explicitly in a climate change scenario.

- As in previous studies, this review has found that the intensity of extreme storm events is likely to increase despite the fact that there is an overall decrease in the annual rainfall.

- Climate change modelling also suggests that there could be a significant increase in the magnitude of PMP events, with increases of up to 30% being suggested. Possible increases of this magnitude should be taken into account in the final design of the Jabiluka water management system by increasing the height of exclusion bunds. This is an action that can be incorporated at the detailed design stage.

5 Storage of uranium on the surface

5.1 Introduction

The issues to be addressed in this chapter relate to the risks associated with the storage of uranium in a stockpile within the Total Containment Zone at Jabiluka. The risks are, essentially, twofold;

(a)   the risk to the environment arising from a sufficiently intense weather event that the capacity of the water retention pond for the catchment of the uranium ore stockpile is exceeded, and

(b)   the risk to the environment associated with the failure of the pond structure itself.

Assessment of the first issue will bring together the hydrological information in the previous two chapters to enable a detailed assessment of the probability of exceeding the available storage capacity for a given design of retention pond. The risk to the environment will then be assessed using site specific information on water chemistry, ecotoxicology and radiation exposure.

Assessment of the second issue will rely upon estimated risks of dam failure for the type of design proposed by ERA for the retention pond followed by a risk assessment that again uses the above site specific information.

It must be recognised that the hydrological modelling described in this chapter does not apply to the actual design of the facility that may be constructed at Jabiluka. This is because the Minister for the Environment did not approve the project as proposed by ERA in the Public Environment Report for the Jabiluka Mill Alternative. As stated earlier, the Minister required the disposal of all tailings in the mine void and additional stopes/silos and required ERA to prepare an amended proposal for the approval of the authorities. ERA is currently preparing the amended proposal.

The Supervising Scientist has chosen to assess the Jabiluka Mill Alternative–Original Concept as described in the PER but with the exclusion of the tailings ponds in that proposal. The reason for this choice is that the modified Original Concept is likely to be very similar to the amended proposal from ERA and because the results of modelling in this review can be compared quantitatively with the results obtained by ERA in the PER. Thus, this chapter does not provide a detailed design of the water management system at Jabiluka. However, the results obtained should be taken into account in such a detailed design by ERA.

5.2 Probability of exceedence of retention pond capacity

5.2.1 Design criterion

The design criterion proposed by ERA in the EIS (p 4–67) for the water management system at Jabiluka was that, to maintain a policy of no release of water from the Total Containment Zone, the retention pond system should be designed to contain runoff from a theoretical extreme Wet season with a 1 in 10,000 annual exceedance probability. This would give a probability for exceeding the retention pond capacity of 0.01% in any single year of operation and an exceedence probability over the 30 year life of the mine of approximately 0.3%.

However, the EIS goes on to state that the system should also include a residual volume of water from the previous year and the water balance modelling considered a sequence of Wet seasons including the 1:10,000 AEP rainfall year. Thus, the pond volume exceedence

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probability over the life of the mine was not quantified but it would be expected to be less than 0.3% and probably about 0.1%.

In both the Supplement to the EIS and the PER, ERA used Monte Carlo calculations to simulate 10,000 years of rainfall and then chose specific extreme sequences of wet years to determine the maximum storage required. The probability of the occurrence of the particular sequences used was not quantified but would be expected to be considerably less than 0.1% over the life of the mine and may have been expected to approach 0.01%.

The approach that has been adopted in this review has been to determine the storage volume required to achieve a range of exceedence probabilities and then to perform a risk assessment for the protection of people and downstream ecosystems. The range of exceedence probabilities calculated is from about 10% to 0.002% over the life of the mine. The lowest value was chosen to ensure adequate precision for the storage volume required to achieve an exceedence probability of 0.01%. This procedure is one that not only enables the adoption of a risk assessment approach but it also enables a quantitative comparison with the outcomes of the results obtained by ERA.

5.2.2 Water balance modelling

Water balance modelling has been carried out by the University of Melbourne (Chiew & Wang 1999, Attachment D) to assess the Jabiluka Mill Alternative–Original Concept as described in the PER but with the exclusion of the tailings ponds in that proposal. The reason for this choice is, as stated above, that the modified Original Concept is likely to be very similar to the amended proposal from ERA and because the results of modelling in this review can be compared quantitatively with the results obtained by ERA in the PER.

The catchment areas within the Total Containment Zone, including the pond area of 9 ha, water input from mine dewatering and the water losses through mill consumption, ore and plant washdown, evaporation in the mine ventilation system and dust suppression were assumed to be those estimated by ERA in Appendix B1 of the PER.

Ventilation system evaporative losses
The feasibility of achieving the predicted losses by evaporation in the mine ventilation system has been assessed in section 3.4 where it was concluded that, unless a very expensive humidifier system is installed, the actual losses will be less than assumed by ERA. Nevertheless, ERA's estimates have been used in the modelling, partly because the modelling was being carried out simultaneously with the assessment of mine ventilation losses, but also because it was considered important to use ERA's assumptions so that a meaningful comparison with ERA's conclusions could be achieved.

In the ERA water balance simulations, a constant ventilation loss was assumed throughout the year. However, the evaporation potential through the ventilation system is greater in the Dry season than in the Wet season because of the greater moisture deficit in the Dry season. This was taken into account by attributing 16% of the total water disposal from the ventilation system to the four wettest months (December to March) and the remaining 84% to the other months, as suggested in the Jabiluka PER Appendices (page B1–9).

Runoff
The runoff calculations used by ERA in its hydrological modelling were assessed by Chiew and Wang (1999) and it was concluded that they were very conservative. The same runoff coefficients were, therefore, used in the current review. However, Chiew and Wang (1999) used a water balance model to simulate the rainfall-runoff process in which the soil water storage capacity is the only parameter, and this parameter is optimised such that the total

runoff is the same as that estimated using the above runoff coefficients. Although the total estimated runoff is the same, the model allows for higher runoff coefficients during wet periods because the soil is closer to saturation.

Pond evaporation

Based upon the analysis presented in section 3.3, monthly evaporation data were obtained from the Jabiru Airport record for pan evaporation from 1971 to 1998 and the application of the pan factors of Vardavas (1987). A very simple algorithm, which included the results presented in section 3.3 on the cross-correlation between monthly rainfall and monthly evaporation, was used to generate monthly pan evaporation data. The monthly pan evaporation data generation algorithm is described in Appendix B of Chiew and Wang (1999). The monthly pan coefficients of Vardavas (1987) were then applied. Daily variation in evaporation within a given month was not considered in the water balance simulation.

To evaluate the algorithm, statistics from 1000 years of generated monthly pan evaporation were compared with the statistics from the observed data. Table 5.2.1 summarises the monthly statistics; a summary of annual statistics is presented in Chiew and Wang (1999). The generated data closely reproduce the observed mean and coefficients of variation for all monthly and annual values. The skewness is not well reproduced because of the large uncertainties in the skewness estimated from only 27 years of observed data. This is reflected in the irregular fluctuation of skewness from month to month. In any case, the skewness in the data is not important because of the relatively small coefficients of variation.

The cross-correlation between the generated annual pan evaporation and rainfall is – 0.41 in close agreement with the observed cross correlation of – 0.43.

Table 5.2.1 Comparison of key monthly pan evaporation statistics in the generated and observed data

	Mean (mm)		CV		Skewness	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
All data	218	219	0.20	0.19	0.29	0.27
Jan	184	186	0.13	0.12	-0.11	0.01
Feb	156	151	0.15	0.13	0.10	-0.13
Mar	175	175	0.11	0.12	0.61	-0.06
Apr	203	204	0.11	0.11	0.11	-0.20
May	216	216	0.07	0.07	-0.22	-0.41
Jun	204	205	0.07	0.07	0.65	-0.06
Jul	216	216	0.08	0.08	0.72	-0.09
Aug	247	247	0.07	0.07	0.19	-0.03
Sep	268	268	0.08	0.08	1.02	-0.12
Oct	288	287	0.10	0.10	0.59	-0.44
Nov	244	246	0.11	0.11	-0.05	-0.07
Dec	212	214	0.12	0.12	-0.18	-0.11

Rainfall

On the basis of the assessment presented in section 3.2, the Oenpelli rainfall record from 1911 until 1998 was adopted in the hydrological modelling of the Jabiluka water management system.

The DMM (daily-monthly-mixed) algorithm (Wang & Nathan 1999) described in Appendix A of Chiew and Wang (1999) was used to generate daily rainfall data. The advantages of this algorithm are that it has a small number of parameters (six for each month) and is capable of reproducing key characteristic statistics simultaneously at the daily, monthly and annual time periods.

To evaluate the DMM algorithm, statistics from 1000 years of generated daily rainfall data were compared with the statistics for the observed data. Table 5.2.2 summarises some of the daily statistics. The table shows that the generated data closely reproduce the observed statistics, including the skewness which is not used in the model fitting.

Table 5.2.2 Comparison of key daily rainfall statistics in the generated and observed data

	Mean (mm)		CV		Skewness	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
All data	3.82	3.81	3.02	3.05	5.52	5.52
Jan	10.90	10.95	1.66	1.69	3.28	3.28
Feb	11.33	11.26	1.58	1.60	3.15	3.14
Mar	9.00	9.01	1.90	1.92	3.58	3.58
Apr	2.60	2.63	3.79	3.89	8.02	8.00
May	0.46	0.44	8.08	7.13	12.16	12.15
Jun	0.05	0.04	16.99	16.94	31.60	31.64
Jul	0.08	0.06	20.55	16.15	25.76	25.79
Aug	0.03	0.01	20.79	23.01	40.85	40.10
Sep	0.16	0.11	11.12	12.00	21.52	21.48
Oct	0.86	0.84	5.92	5.37	12.18	12.13
Nov	3.60	3.59	2.68	2.70	4.96	4.96
Dec	7.19	7.21	2.02	2.02	3.65	3.66

The monthly and annual statistics are presented and assessed in Chiew and Wang (1999). Overall the model reproduces the monthly statistics very well with minor unimportant variations in the Dry season. The annual mean and the coefficient of variation are almost exactly reproduced but a small positive skewness is produced in the generated data while the observed skewness is almost zero. This could tend to produce higher rainfalls in very wet years and is therefore conservative.

5.2.3 Estimation of required storage capacity under current climatic conditions

Daily simulation of the storage water balance is given by

$$S_{t+1} = S_t + Inflows - Losses$$

where S_t is the present storage and S_{t+1} is storage on the following day. The inflows into (runoff and mine dewatering) and losses from the storage (evaporation, mill requirement, ore wetdown and ventilation loss) were as described above. All the losses were subtracted from the storage as long as there was water in the retention pond.

Fifty thousand runs were carried out, with each run simulating the daily storage water balance over a 30-year mine life, starting with an empty pond. The largest accumulated storage in each run gave an estimate of the storage capacity required such that the retention

pond capacity would not be exceeded in that run. The largest of these 50,000 values is, therefore, the estimate of the storage capacity with a 0.00002 (1:50,000) probability of being exceeded during the 30-year mine life. The tenth largest of these values is the estimate of the storage capacity with a 0.0002 (or 0.02%) probability being exceeded in the 30-year mine life, and so on.
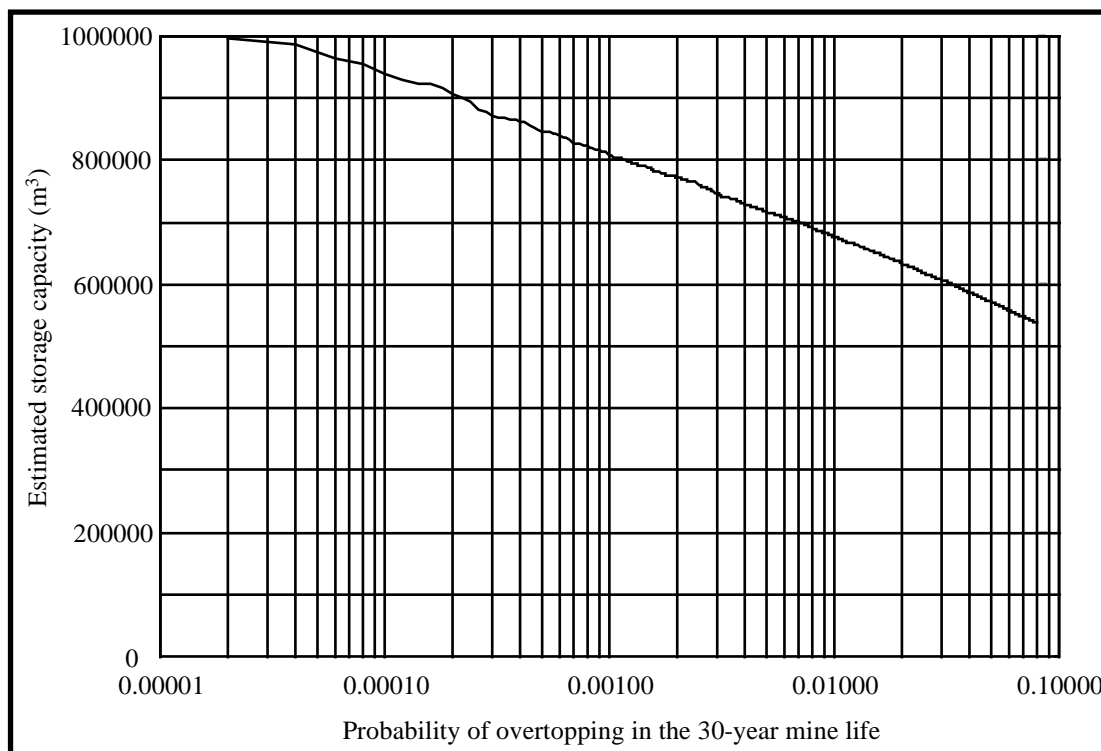
Figure 5.2.1 Estimates of storage capacity required as a function of exceedence probability over the 30-year mine life under current climatic conditions

Figure 5.2.1 shows the estimates of storage capacity required as a function of exceedence probability over the life of the mine. The volume of pond proposed by ERA in the PER was 810,000 m^3. (This is based upon a 9 ha pond of depth 9.5 m (PER p 4–52) of which 0.5 m is freeboard required to take into account wave action and is therefore not available for storage except under emergency conditions.) The data in figure 5.2.1 indicate that the probability of this storage capacity being exceeded in the life of the mine would be about 1:1,000. Based on these simulations, the estimate of storage capacity required to achieve an exceedence probability of 0.01% (1 in 10,000) over the 30-year mine life is 940,000 m^3 (an equivalent depth of 10.4 m in the 90,000 m^2 storage area).

Comparison of model with that used by ERA

There are several differences between the approach adopted in this review by Chiew and Wang (1999) and the approach used by ERA to estimate the required storage capacity (described in Appendix B1 in the Jabiluka PER Appendices).

In the ERA approach, 10,000 years of annual rainfall data were generated using a log-normal distribution. A 15-year water balance simulation was carried out using a typical 15-year sequence to provide a base data set. Ten simulations were carried out — with the first year of the base data replaced with the wettest of the 10,000 years of the generated rainfall, with the first two years of the base data replaced with the wettest two-year sequence, with the first

three years replaced with the wettest three-year sequence, up to the first ten years replaced with the wettest ten-year sequence.

The simulations were carried out on a monthly time step, with the annual rainfall data distributed over the 12 months using the same monthly factors for all years of simulations (see table B1.1 in the Jabiluka PER Appendices). Mean monthly storage evaporation rates were used for the simulations (calculated using Hatton's (1997) pan coefficients times the mean monthly pan evaporation — see discussion in section 3.3). The other water use considerations were similar to those used here except for evaporative losses in the ventilation system (see section 5.2.2).

The use of a 15-year water balance simulation by ERA instead of a 30-year simulation is, to a large extent, reasonable because the full evaporative capacity of the ventilation system is not available until the tenth year of operation and, therefore, the storage capacity is most likely to be exceeded in the first few years. (This issue will be further addressed in section 5.2.5.) This is probably also the reason why ERA replaced the first years of the base data with the wettest sequence to mimic the extreme wet conditions.

The significance of the other differences between the approach adopted by ERA and that used in this review is assessed below using a sensitivity analysis.

5.2.4 Sensitivity analysis

It is difficult to carry out a direct comparison between the ERA approach to hydrological modelling and that used for this review. However, Chiew and Wang (1999) investigated the sensitivity of the required storage capacity to each of the variables for which different assumptions were made by ERA and Chiew and Wang (1999).

For the purpose of the sensitivity analysis, the full simulation procedure described in section 5.2.3 was not adopted since it would have been extremely demanding on computer time. Rather, the model was run a number of times using the actual rainfall and evaporation data recorded during the period September 1972 and August 1998. Six water balance calculations were carried out using a monthly time step and three calculations were carried out using a daily time step. Within these subsets, the procedure adopted to determine rainfall, pond evaporation, evaporation losses in the ventilation system and runoff were varied as indicated in table 5.2.3. Values of the largest storage capacity required in each of the nine model runs are tabulated in table 5.2.3; the results are discussed below in terms of the significance of the assumptions made. While this procedure is not as thorough as running the full simulation in each case, the results should be adequate to assess the relative significance of each assumption.

Interannual variability in evaporation and the correlation between evaporation and rainfall
Runs 1 and 2 are the same except for the use of pan evaporation data. Run 1 uses the actual monthly pan evaporation data while in Run 2 the mean monthly pan evaporation rates, averaged over the 26 years, are used. Run 1 therefore takes into account the interannual variability in evaporation and the correlation between evaporation and rainfall while Run 2 does not. The results in table 5.2.3 indicate that ignoring the interannual variability in evaporation and the correlation between evaporation and rainfall results in a 3% underestimate of the required storage capacity.

Actual rainfall versus monthly distribution of annual rainfall
Runs 1 and 3 differ only in the use of rainfall data. Run 1 uses the actual monthly rainfall data, while in Run 3 the annual rainfall is distributed over the 12 months using the monthly factors in table B1.1 in the Jabiluka PER Appendices. The use of the actual monthly rainfall

data results in a higher storage capacity estimate because the rainfall in some months can be significantly greater than the monthly rainfall calculated as a proportion of the annual rainfall using a typical distribution through the year. The results in table 5.2.3 indicate that the use of a typical distribution to proportion the annual rainfall to individual months rather than actual or simulated monthly rainfall results in a 1.7% underestimate of the required storage capacity.

Table 5.2.3 Largest storage capacity required as a function of the assumptions used in the hydrology model

	Rainfall data	Pan evaporation data	Ventilation loss	Runoff estimation	Largest storage (m^3)
Monthly simulation					
1	Actual data	Actual data	Same for each month	Runoff coefficient	582,944
2	Actual data	Long-term monthly average	Same for each month	Runoff coefficient	565,939
3	Fixed distribution of annual rainfall	Actual data	Same for each month	Runoff coefficient	573,145
4	Actual data	Actual data	Lower in Wet season	Runoff coefficient	589,744
5	Actual data	Actual data (Hatton's pan factor)	Same for each month	Runoff coefficient	568,502
6	Actual data	Long-term monthly average (Hatton's pan factor)	Same for each month	Runoff coefficient	540,962
Daily simulation					
7	Actual data	Actual data	Same for each month	Runoff coefficient	591,188
8	Actual data	Actual data	Same for each month	Conceptual storages	587,515
9	Actual data	Actual data	Lower in Wet season	Conceptual storages	593,812

Constant ventilation loss versus smaller ventilation loss in the Wet season

Runs 1 and 4 differ only in the ventilation loss calculations. Run 1 uses a constant ventilation loss throughout the year (as in the ERA approach) while Run 4 takes into account that the ventilation losses would be lower in the Wet season than in the Dry season. The assumption of constant ventilation system losses throughout the year leads to a 1.2% underestimate of the required storage capacity.

Pan evaporation coefficients

Run 1 uses the pan evaporation factors recommended in section 3.3 while Run 5 uses the pan factors given by Hatton (1997) and adopted by ERA. The factors are the same except for two months. The estimate of the storage capacity required is about 2.5% higher when the recommended pan factors are used.

Daily versus monthly simulation

Runs 1 and 7 differ only in the simulation time step. The use of a larger time step is expected to give rise to an underestimate of the required storage capacity because inputs to the system (rainfall) can vary rapidly on a daily basis but outputs or losses (evaporative losses and mill consumption) are fairly constant on a daily basis. The results in table 5.2.3 indicate that the use of a monthly time step may result in a 1.4% underestimate of the required storage capacity.

Runoff coefficient versus conceptual rainfall-runoff modelling

Runs 7 and 8 are the same except for the method used to estimate surface runoff. In Run 7, surface runoff is estimated using a runoff coefficient multiplied by rainfall while in Run 8 surface runoff is simulated using a conceptual rainfall-runoff model, with the soil capacity parameter optimised to produce the same total runoff as in Run 7. The results in table 5.2.3 indicate that the use of constant runoff coefficients results in a small overestimate (about 0.4%) of the storage capacity required.

Overall effect of the various assumptions used by ERA

Although the effect of each of the individual assumptions discussed above is quite small, in most cases the result is an underestimate of the required storage capacity and the cumulative effect of these assumptions could be significant. This is illustrated in the comparison of the results obtained in Runs 6 and 9. In Run 6, the ERA assumptions have been used within the framework of the water balance model described in this review whereas Run 9 uses the assumptions described in this report. The results in table 5.2.3 indicate that the combined effect of the use of ERA's assumptions may lead to a 10% underestimate of the storage capacity required for a given design criterion. If the pond volume proposed by ERA, 810,000 m³, is increased by 10%, the exceedence probability obtained from figure 5.2.1 is about 0.0002, ie 1 in 5000, over the life of the mine.

There were, as noted in section 5.2.3, other differences in the modelling approach adopted by ERA in that, instead of performing a full Monte Carlo calculation of the response of the catchment to rainfall, ERA performed a Monte Carlo calculation of annual rainfall and then selected particular sequences of Wet seasons to simulate the response of the catchment. The pond capacity derived by ERA on this basis was only 706,000 m³. ERA then added additional capacity to ensure that adequate storage would be available in subsequent years but there was no clear indication of what exceedence probability was expected to be achieved using the final total capacity of 810,000 m³.

5.2.5 Use of pond evaporation rather than evaporation in the ventilation system

Chiew and Wang (1999) investigated the demands on storage capacity as a function of time during the life of the Jabiluka project. As was the case for the sensitivity analysis described above, the full simulation procedure described in section 5.2.3 was not adopted since it would have been very demanding on computer time. Instead, the model was run using the actual rainfall and evaporation data recorded during the period September 1972 and August 1998.

The results of these calculations are presented in figure 5.2.2. The plots show the annual rainfall in the Oenpelli record for the period and the accumulated water volume calculated by the model at the end of each month during the period.

The data presented in figure 5.2.2 show that the largest volume of accumulated water calculated by the model for the period is 594,000 m³. A storage capacity of about 600,000 m³ would, therefore, have been required to avoid exceedence at any time during the 26-year period using the actual recorded rainfall. Note that this volume is much lower than would be required for, say, a 1:10,000 exceedence probability if one used the rainfall records for this period as the basis for a Monte Carlo simulation of the type described in section 5.2.3.

The largest accumulated volume of water occurred in the fifth year of this simulation following a steady build-up during the previous four years. After this peak volume is reached, the maximum volume required decreases in subsequent years until, following the simulated tenth year of operation, the maximum capacity required in all years is less than half the maximum value. Indeed, on a number of occasions, the volume of stored water reduces to

zero, implying that water would need to be imported from the bore field to enable continuation of the milling process.

Examination of the annual rainfall record presented in figure 5.2.2 shows that this characteristic, which is typical of all simulations, is not attributable to an unusually high sequence of wet years in the early part of the rainfall record. Rather, the observed pattern is due to the gradual increase in assumed losses due to evaporation in the ventilation system (and, to a much less significant extent, losses due to ore wet-down and plant wash-down) which only reach their maximum value in year 10 of operation. The water losses assumed in the calculations, taken from the PER Appendix B1 are given in table 5.2.4.
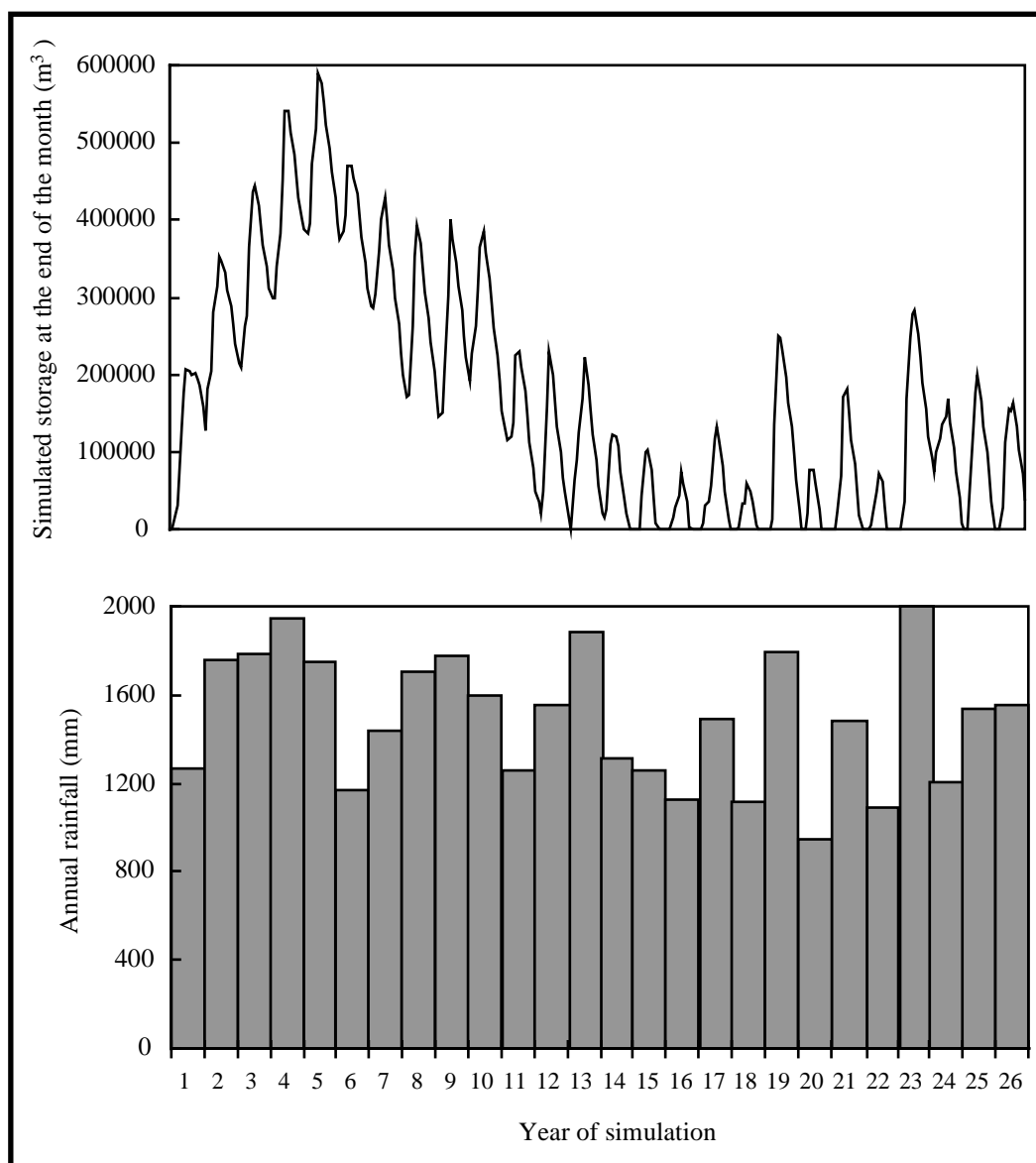
Figure 5.2.2 Annual rainfall (September – August) and accumulated water volumes for a model simulation using actual rainfall and evaporation from September 1972 to August 1998

Evaporation in the ventilation system was examined in section 3.4. It was shown there that, unless an expensive humidifier system is installed, the maximum loss by evaporation in the ventilation system would be about 40% of the value proposed in the EIS and the PER. It was suggested that this deficiency could be overcome by increasing the area of the retention pond

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by about 4 ha, thus increasing its evaporative capacity. If this suggestion were to be implemented, then the full additional evaporative capacity of 90,000 m³ would be available as soon as water covers the base of the retention pond. By year 5 of operation, the difference in accumulated water losses from the water management system between this scenario and that outlined in table 5.2.4 is about 300,000 m³. Hence, the maximum storage capacity required in the simulation illustrated in figure 5.2.2 would be reduced by about 50%. Similarly, it is likely that if the full simulation of the water management system were repeated using pond evaporation rather than evaporation in the ventilation system, the capacity required to achieve an exceedence probability of 0.01% over the life of the mine (see section 5.2.3) would be reduced by about 30%.

This 30 % reduction in the required water storage capacity of the Jabiluka retention pond far outweighs the increase of about 10% that arises from consideration of refinements in the hydrological modelling that were addressed in the previous section. It is recommended that ERA, in its detailed design of the Jabiluka water management system, uses increased pond evaporation rather then enhanced evaporation in the ventilation system to minimise the volume of the water retention pond. In making this recommendation, it is recognised that some enhanced evaporation in the ventilation system as a result of dust suppression procedures is inevitable. This will need to be modelled carefully by ERA to achieve the optimum water management system.

One advantage of the original ERA proposal to use enhanced evaporation in the ventilation system was that its use would be under control and, for example, in drier years or sequences of years, pond water levels could be controlled by switching off the enhanced evaporation system and minimising the need to import water from the bore field. If only pond evaporation is used, this level of control is lost. One way of retrieving control would be to partition the water retention pond into three or four compartments with connecting spill ways and a water pumping system. In this way evaporative losses in dry spells could be minimised by pumping all remaining water into one of the compartments and could be maximised in wetter periods by using the full evaporative capacity of all of the compartments. It is recommended that ERA consider this approach in the detailed design of the water management system at Jabiluka.

Table 5.2.4 Water losses assumed in the hydrological model of the Jabiluka water management system (annual volumes in m³). Data from JMA Public Environment Report, Appendix B1.

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11–30
Evaporation	Variable (see section 3.3) but approximately 170,000										
Mill requirement	0					180000					
Ore wet-down and plant wash-down	800	1200		3500				7000			10000
Mine ventilation and dust suppression	0	15000	30000	45000	60000	75000		90000			

5.2.6 Effect of climate change on the required water storage capacity

In section 4.4.2, the principal conclusions on the effect of possible climate change over the next 30 years were that:

- The projected temperature increase in the region of Jabiluka is expected to be in the range 0.35–0.8ºC.

- The predictions for change in the Wet season rainfall in the region range from +1% to - 6%.

- The intensity of extreme storm events is likely to increase despite the fact that there is likely to be an overall decrease in the annual rainfall.

It was also found that decadal scale variability was significant and that there exists in the historical record a small long-term upwards trend in the mean annual rainfall but it was concluded that both of these effects are included in the stochastic rainfall model used to assess the required water storage capacity at Jabiluka and need not be considered further.

The minimum predicted temperature increase is the extreme scenario for water balance modelling since this would minimise evaporation and hence maximise the required storage volume. The minimum predicted increase of 0.35ºC over the next 30 years is insufficient to have any significant impact on evaporation. There is no need, therefore, to adjust the hydrological model to take the effect of temperature change into account.

The maximum predicted change in annual rainfall from global warming over the next 30 years is 1%. There is, therefore no need to repeat the simulation of the water management system presented in section 5.2.3 to take this effect into account. The effect of climate change will be negligible.

The climate change model DARLAM predicts (Jones et al 1999) that storm intensity will increase over the next 30 years. DARLAM simulates little change in annual rainfall over Jabiluka by the year 2030, but extreme rainfall becomes about 10% stronger and the present 1-in-10 year event becomes a 1-in-7 year event. Even in the main months of the Wet season (December until February) when average rainfall is predicted to decrease by about 3%, extreme rainfall is predicted to increase by about 5%. The largest changes are predicted to occur at the junction of the Wet and the Dry seasons (March until May) when it becomes about 30% wetter on average, extreme rainfall intensities rise by up to 24% and extreme events double in frequency. It should be noted, however, that of the six models used to assess climate change (see table 4.3.3), DARLAM is the model that predicts the highest positive changes in mean rainfall in both the Wet and Dry seasons.

The effect of the predicted change in storm intensity can be assessed by examining the results obtained in section 5.2.4 in which the results of a sensitivity analysis were presented. The difference in required storage volume between the use of a daily time step in the model and that obtained from the use of a monthly time step was 1.4%. This result was obtained for the same total rainfall in each month. The predicted increases in storm intensity arising from global warming would have the effect of increasing the rainfall on a daily basis but decreasing the overall monthly figure. The results of the sensitivity analysis, therefore, indicate that the increase in storm intensity predicted by the global warming model would not have any significant impact on the required storage capacity of the water management system at Jabiluka.

5.3 Risk assessment for the ERA proposal

In principle, the information derived in the previous section on the probability of exceeding the capacity of any specified water retention pond at Jabiluka could be combined with research results on the environmental impact of the constituents of mine waters to determine the pond capacity required to meet specified environmental protection objectives. These objectives would include ensuring that the radiation exposure of people who consume foods collected from downstream waterbodies would be below the recommended international limits on radiation dose. They would also include specifications on the upper limits for

concentrations of a range of important constituents of the effluent to ensure a very high level of ecosystem protection.

Implicit in this approach, however, is the assumption that significant quantities of water could regularly be discharged from the mine site provided that the appropriate standards are met. While this might be sound on a scientific level, the Aboriginal people of the region have been consistent in their opposition to the discharge of mine waters and, because of these deeply felt concerns, ERA has adopted a policy of not releasing any water from those parts of the mine site containing the mill, ore stockpiles and any material with a concentration of uranium of greater than 0.02%. Only inert waste rock would be outside this Total Containment Zone. Thus the size of the pond has been determined on social grounds rather than scientific grounds.

The issue that will be addressed in this section is the quantification of the risk to people and downstream ecosystems arising from any particular choice of storage capacity. In particular, we will assess the risks associated with the particular storage pond proposed by ERA in the Public Environment Report. This will be followed by an assessment of the risk associated with dam failure.

5.3.1 Water quality of runoff from the ore stockpile

Prior to estimating the risks associated with discharges of water from the ore stockpile to the environment beyond the mine site, it is necessary to estimate the concentrations of the principal constituents in runoff water.

In Appendix B1 of the PER, ERA reviewed the information available on runoff water quality. It identified the principal constituents as uranium and its radioactive progeny, and magnesium sulphate. The information obtained from kinetic testing of a number of samples of the Jabiluka ore showed that, while a number of metals and metalloids were present in the ore at concentrations greater than average in the earth's crust, none other than uranium was at a concentration that, under the general chemical environment of the ore stockpile, will present a threat to ecosystems or people beyond the mine site. The Supervising Scientist agrees with this assessment.

ERA, based upon a review of water quality in the ore stockpile sump at Ranger, estimated that concentrations of uranium in runoff water are likely to be in the range 5000 – 10,000 µg/L. Based upon the concentrations of uranium in the sump in recent years, this estimate appears to be valid. However, in earlier years of the Ranger operation, concentrations as high as 50,000 µg/L were observed. In addition, it is necessary to take into account the higher concentration of uranium in the ore at Jabiluka (0.46%) compared to that at Ranger (0.3%). On this basis, a value of 80,000 µg/L has been adopted as a worst case scenario for this risk assessment. This converts to 1000 Bq/L in radioactivity units.

ERA estimated the concentration of [226]Ra at 100 mBq/L based upon relatively infrequent measurements of radium concentrations in the stockpile sump at Ranger. While this may well be a reasonable estimate, a more conservative approach has been adopted in this review. The concentrations of all of the other long-lived radionuclides of the uranium series in runoff from the Jabiluka ore stockpile have been estimated using the observed ratios of the concentrations of these radionuclides (Martin et al 1998) to concentrations of uranium in Retention Pond No 2, which collects water from the ore stockpiles and water transferred from the mine pit at Ranger.

Table 5.3.1 Estimates of the maximum concentrations of the prinipal constituents in runoff from the ore stockpile at Jabiluka

Chemicals	Concentration mg/L	Radionuclides	Concentration Bq/L
Uranium	80	^{238}U	1000
Magnesium	500	^{234}U	1070
Sulphate	2,000	^{230}Th	3
		^{226}Ra	340
		^{210}Pb	20
		^{210}Po	3

ERA estimated that the electrical conductivity, dominated by magnesium and sulphate ions, would be in the range 3000–5000 μS/cm. The upper limit of this range corresponds to concentrations of magnesium and sulphate of 500 mg/L and 2000mg/L respectively. The Supervising Scientist has recently carried out solute modelling for the waste rock dumps at Ranger (leGras & Klessa 1997). This work showed that $MgSO_4$ mobilisation occurs at a rate similar to the rate of erosive degradation of the schist. That is, there is an initiation period after rock placement of about 3 years during which little solute is released. According to the proposed Jabiluka mine plan, ore and waste rock will be stored for an insufficient period for significant solute evolution. The Supervising Scientist, therefore, believes that the concentrations of Mg and SO_4 that will occur in runoff from the ore stockpile at Jabiluka will be significantly lower than the estimates provide by ERA. Nevertheless, to ensure that a conservative estimate is obtained in the risk assessment, the concentrations of $MgSO_4$ have been taken to be the highest values estimated by ERA.

A summary of the concentrations of the principal constituents in runoff from the Jabiluka ore stockpile used in the risk assessment are provided in table 5.3.1. It is stressed that all of these concentrations are considered to be maximum expected values and some are likely to be significant over-estimates.

5.3.2 Radiation exposure of members of the public

The probability of exposing members of the public to a particular radiation dose can be derived from the probability with which a specified volume of water will, under extreme climatic conditions, need to be discharged to Swift Creek downstream from the mine and the calculation of the radiation dose that will result from that discharge.

As stated in section 5.2.3, the storage capacity of the retention pond proposed by ERA in the PER was 810,000 m^3. From the results of the Monte Carlo simulation methods shown in figure 5.2.1, the probability of the occurrence of water volumes in excess of the pond capacity can be derived. These results are shown in figure 5.3.1.

Estimates of radiation exposure of members of the public resulting from discharges of radionuclides in water from the Ranger mine have been made by the Supervising Scientist (Johnston 1990) based upon a model of dispersion of radionuclides in the Magela Creek system, the diet of the critical group, and results of research on the uptake of uranium series radionuclides in food items from the waters and sediments of the Magela system (Johnston et al 1997). The model has recently been updated by Martin et al (1998) to take into account all recent research results and the most recent recommendations of the International Commission on Radiological Protection on dose conversion factors (ICRP 1996).
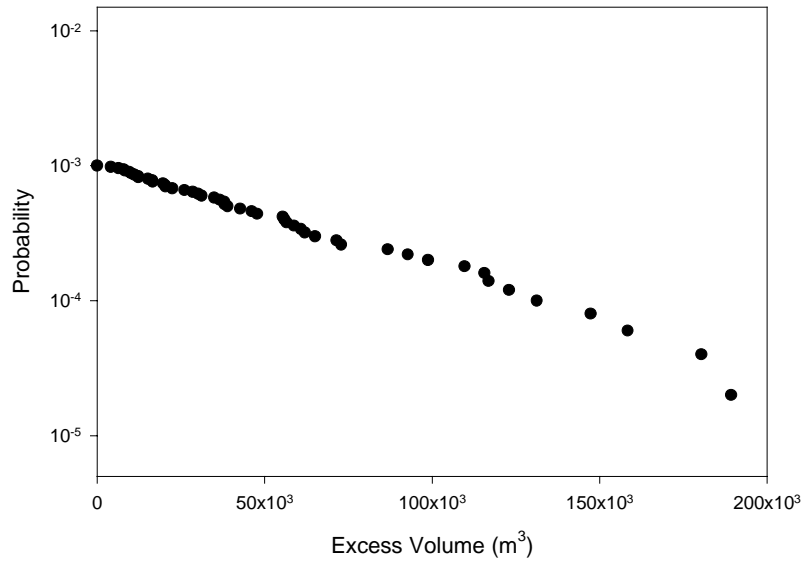
Figure 5.3.1 Probability of occurrence of excess water volumes in the Jabiluka Total Containment
Zone over the life of the mine for the storage capacity specified by ERA

A model for assessing the radiation dose resulting from discharges of radionuclides from Jabiluka will be different from the Ranger model, principally in the radionuclide dispersion part of the model. However, the difference will be relatively small and the Ranger model has been applied here.

The dose estimates arising from the excess volumes predicted by the Monte Carlo analysis of the Jabiluka water management proposed by ERA lie in the range 0 to 27 μSv. These estimates take into account that runoff from the ore stockpile only contributes 1% of the total water flowing from the TCZ to the retention pond. The probability of occurrence of these doses over the 30 year life of the mine are presented in figure 5.3.2.
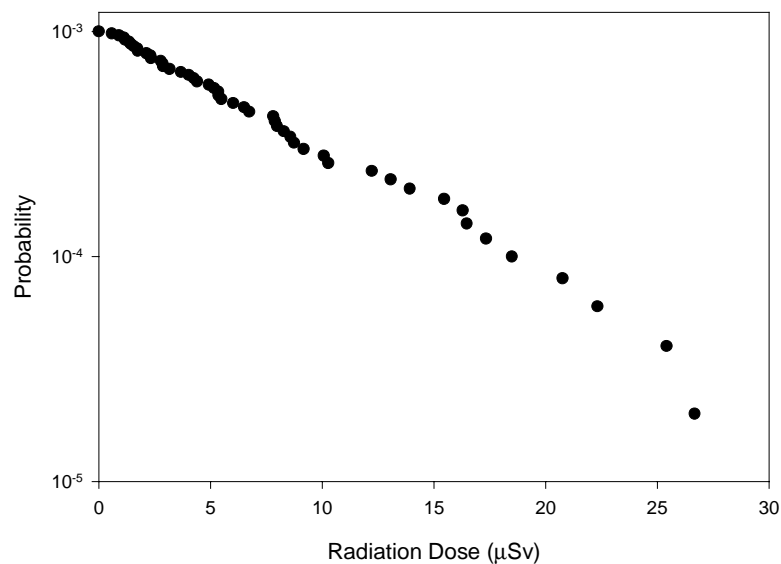
Figure 5.3.2 Probability versus radiation exposure of members of the public resulting
from the discharge of excess water from the Jabiluka mine site for the water
management system proposed by ERA

Thus the probability that any member of the public would receive a radiation dose of 20 µSv on one occasion during the 30 year life of the mine would be less than 1 in 10,000. The annual dose limit recommended by the ICRP for members of the public is 1000 µSv per annum. The conclusion of this analysis is, therefore, that the water management system proposed by ERA for Jabiluka is one that poses an insignificant radiological risk to people living in the vicinity of the mine and consuming traditional foods obtained from the waterbodies downstream from the mine.

5.3.3 Impact on aquatic ecosystems

The discharge of excess waters from the Jabiluka mine site could, in principle, give rise to impact on aquatic ecosystems through both radiological and chemical exposure.

Radiological exposure

The Supervising Scientist conducted an assessment (Johnston 1989) of the probable radiological impact on aquatic animals of the Magela Creek and Magela floodplain resulting from the discharge of water from Retention Pond No 2 at Ranger into the Magela Creek. For acute exposure, it was found that the expected dose for fish and macroinvertebrates would be about three per cent of the lowest dose at which any effect had been reported in the literature using sensitive endpoints such as reproductive capability, embryo survival, growth rate etc. For all other animals, acute doses would have been lower by another order of magnitude.

For chronic exposure, the results for fish showed that the maximum expected dose rate was less than one per cent of the lowest observed effect dose rate but for invertebrates it was about twenty per cent. However, the lowest observed effect rate for invertebrates had been deduced from an experiment where other contaminants were present in the water and it should therefore be treated with caution. The next lowest value for invertebrates in the literature was higher by a factor of about 40.

The total discharged loads of each of the radionuclides of the uranium series considered by Johnston (1989) were higher by a factor of about 10 than the loads that would be discharged from the Jabiluka site at the 1 in 50,000 probability level shown in figure 5.2.1. The conclusion of this analysis is, therefore, that the water management system proposed by ERA for Jabiluka is one that poses an insignificant radiological risk to aquatic animals which live in waterbodies downstream from the Jabiluka mine.

Chemical exposure

A risk analysis for chemical exposure of aquatic animals is more complex than for radiation exposure of people because the principal risk is that concentrations (rather than annual loads) of chemicals reach a threshold value at which aquatic organisms are harmed. The increase in the concentration of a chemical in Swift Creek downstream from the mine will depend upon the dilution available for waters leaving the mine site arising from existing flow in the Creek.

In general, since the catchment of Swift Creek is quite small, about 40 km^2, a significant rainfall event that affects the mine site will also affect most of the catchment. In this case, the dilution available for waters flowing from the mine site will be determined by the ratio of the mine site area to that of the whole catchment of Swift Creek, taking into account the respective runoff coefficients. Thus the dilution in Swift Creek will be given by:

$$D = A_c r_c / A_s r_s$$

where A_c and r_c are the area and the runoff coefficient for the whole Swift Creek catchment and A_s and r_s are the corresponding figures for the ore stockpile. To be conservative, the

runoff coefficients for the stockpile and the whole catchment have been assumed to be 1.0 and 0.4 respectively although towards the end of a Wet season with an exceedence probability of greater than 1:1,000 the runoff coefficient for the whole catchment would also probably be approaching 1.0. The areas of the catchments have been taken as 40 km^2 for Swift Creek and 2500 m^2 for the ore stockpile as specified in the PER. These figures yield a dilution factor of about 6400.

As indicated in section 5.3.1, the principal constituents of runoff that need to be considered are magnesium, sulphate and uranium.

A number of studies of the toxicity of uranium to local native species of Kakadu National Park have been carried out by the Supervising Scientist and by ERA. These measurements were conducted following an extensive program of research by the Supervising Scientist in which 19 different local native species of aquatic animals and plants were investigated (Holdway et al 1988a) to establish their suitability for incorporation in an ecotoxicological testing program. The species eventually adopted in the program were chosen on the basis of their suitability with respect to rearing and captive husbandry and also with respect to the sensitivity of their response to exposure to waters in the retention ponds at the Ranger mine.

Results for the toxicity of uranium to aquatic animals of the region are given in Holdway et al (1988b), Bywater et al (1991) and Holdway (1992). The lowest concentration of uranium at which any adverse effect was observed (the LOEC) was 190 µg/L and the highest concentration at which no effect was observed (the NOEC) was 160 µg/L. These results were obtained for the Cnidarian *Hydra viridissima* using population growth over six days as the test endpoint. Other work by the Supervising Scientist (Lewis 1992) indicated that the sensitivity of freshwater snails to waters in the retention ponds at Ranger, in which uranium is the most significant constituent, is comparable with that of Hydra.

The regular application of ecotoxicological data is in determining the dilution required to render 'safe' the discharge of an effluent into a stream. In such cases, the approach usually adopted is to apply a 'safety factor' to the geometric mean of the lowest NOEC and the corresponding LOEC to take into account within-species variability, between-species variability and statistical effects (ie Type I vs Type II errors). This approach has been adopted by, and continues to be recommended by, the Supervising Scientist in the application of Best Practicable Technology to the management of water at the Ranger mine (Johnston 1991). The reason for the approach is that, in recommending a safe dilution for an actual release of effluent, the species used in the laboratory are being considered as surrogates for the whole ecosystem and caution needs to be applied to ensure that other aquatic animals will be protected.

The same approach is recommended for risk assessments (van Leeuwen & Hermens 1995, USEPA 1998) to determine the concentration below which no effects on aquatic ecosystems will be expected. Using the data given above for hydra, the safe concentration for uranium is 18 µg/L. In the current assessment, this concentration will be used to indicate the concentration below which no effects are expected. In addition, the lowest observed LOEC in tests carried out on local native species, 190 µg/L, will be used to indicate the concentration above which adverse effects would be expected to occur. For concentrations intermediate between the 'safe concentration' and the 'effects concentration', it is considered that adverse effects may occur in some species, particularly invertebrates.

In this context, it should also be noted that the estimate used for the concentration of uranium in runoff from the ore stockpile (see section 5.3.1) is considered to be a worst case scenario and is about a factor of 10 higher than the estimate made by ERA in the PER based upon

experience at Ranger over the past number of years. We have taken the approach of adopting a conservative value for the concentration of uranium (which is applied to the risk assessment for both radiation exposure of members of the public and for ecosystems) and then being as realistic as possible in assessing the probable effects on people and aquatic animals. Thus, both 'safe' and 'effects' concentrations are considered in the assessment.

Sulphate is a common anion of natural surface waters and is not regarded as a toxic compound. To increase the concentration of sulphate it is necessary to increase the concentration of some cation and it is the toxicity of the cation that needs to be assessed rather than that of sulphate. For these reasons, the Supervising Scientist recommended to the Northern Territory that the receiving water standard for sulphate be set on human health grounds; 200 mg/L was the recommended limit. This is considered to be the 'safe' concentration. No 'effects' concentration has been considered for sulphate since uranium is the dominant toxicant.

Magnesium is not normally considered to be a toxic substance and few studies of its toxicity have been carried out. No recommendation was given for a water quality guideline in the Australian Water Quality Guidelines for Fresh and Marine Waters (ANZECC 1992). In his recommendations to the Northern Territory, the Supervising Scientist noted the limited data on the toxicity of magnesium and recommended a limit of 20 mg/L, a figure that was more than 100 times lower than the reported LC50 value for *Daphnia hyalina* (Baudouin & Scoppa 1974). Of more significance to aquatic animals would be a change in the ratio of magnesium to calcium in the water but this would only be of relevance if the change were prolonged rather than the transient scenario being considered here. The 'safe concentration' is taken as 20 mg/L and, as for sulphate, no 'effects concentration' is considered.

Table 5.3.2 Estimates of concentrations of U, Mg and SO_4 in runoff from the ore stockpile at Jabiluka and the resulting concentrations in Swift Creek under 'normal' and 'extreme' dilution conditions. Also given for comparison are the 'safe' and 'effects' concentrations.

	Stockpile Runoff mg/L	Swift Creek (Normal) mg/L	Swift Creek (Extreme) mg/L	'Safe' Concentration mg/L	'Effects' Concentration mg/L
Uranium	80	0.012	0.11	.018	0.19
Magnesium	500	0.08	0.70	20	na[1]
Sulphate	2,000	0.30	2.8	200	na[1]

1 Not applicable

A summary of the above data is presented in table 5.3.2 where the estimated concentrations of uranium, magnesium and sulphate in Swift Creek resulting from discharge of excess water from the ore stockpile are compared to the concentration limits at which it is estimated adverse effects will be observed. It can be seen that, under the dilution scenario envisaged (Swift Creek Normal in the table), no effect on the aquatic animals living in Swift Creek would be expected to occur even when the volume of excess water discharged is that with an exceedence probability of 1 in 50,000 over the life of the mine.

The above dilution scenario would not apply if the rainfall event is very intense and of short duration. In these circumstances, because of the finite size of the catchment there will be a delay between the rainfall event over the whole catchment and the peak of the stream hydrograph at the catchment outlet point. This implies that the full dilution expected under normal circumstances would not be available because the water from the mine site, which is relatively close to the creek, would not be delayed significantly.

A second dilution scenario has, therefore, been examined in which it is assumed that an extreme rainfall event (with a return period in excess of 1 in 100) occurs at the end of what would already be an extreme rainfall year (1 in 1000). It is also assumed that the event is centred on the TCZ and that the intensity of the storm reduces in magnitude as a function of distance from the TCZ.

The data on such a storm have been derived from the exceptionally severe storm that occurred at Jabiru on 4 February 1980. The storm had a duration of 16 hours with a total rainfall registration of 303 mm at Jabiru East but within the storm there was a remarkably high rainfall burst with a duration of 5 hours and a recorded rainfall of 240 mm. At the time of this event, there were 10 continuously recording streamflow stations operating in the Magela Creek catchment and 21 continuously recording rainfall stations. The amount of data available from this recording network enabled an unusually detailed analysis of the storm to be undertaken by the Water Division of the Northern Territory Department of Transport and Works (Water Division 1982). This analysis used a flood-routing model to extend and reconcile the rainfall pattern with the resultant flood down the Magela Creek and its tributaries.
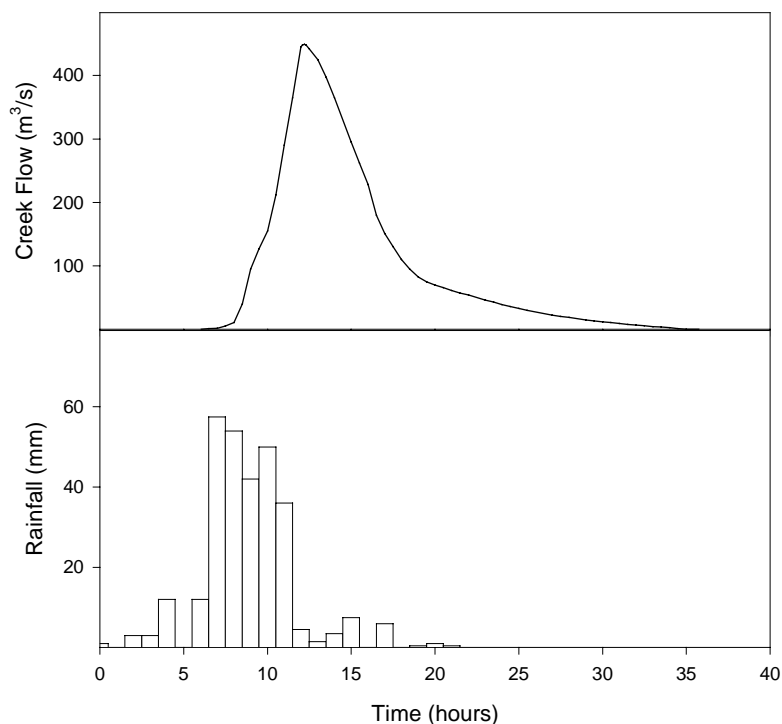
Figure 5.3.3 The hydrograph for Gulungul Creek and the recorded rainfall at Jabiru East near Ranger for the severe storm of 4 February 1980

One of the tributaries of the Magela Creek that was used in the analysis was Gulungul Creek which drains part of the Ranger mine site. The catchment of Gulungul Creek is 46 km^2 which is very close to the catchment size of Swift Creek. The flood hydrograph for Gulungul Creek in response to the storm should, therefore, be a very good analogue for the response of Swift Creek to an unusually intense short storm. The rainfall data and the Gulungul Creek hydrograph are shown in figure 5.3.3. The flow observed in the creek during the 5 hour period when the storm was most intense was only 14% of the total flow over the complete hydrograph. This analysis indicates, therefore, that if water draining the TCZ at Jabiluka reaches Swift Creek without significant delay, the dilution would be reduced to about 900:1.

The Institution of Engineers Australia makes recommendations (Pilgrim 1987) for the values of depth-area ratios to be applied in estimating the effect of the worst case assumption that the storm is centred on the TCZ and that the intensity of the storm reduces in magnitude as a function of distance from the TCZ. For a 40 km² catchment the ratio for a five hour event is about 0.97. However, the Water Division of the NT Department of Transport and Works (Water Division 1982) also derived depth-area curves for the storm of 4 February 1980. The depth-area data and the best fit to these data for the 5 hour period of greatest rainfall intensity are shown in figure 5.3.4. From these data, the rainfall over the whole catchment of Swift Creek could be less than that on the TCZ by up to 20%. Using this more conservative figure, the dilution available in Swift Creek could be as low as 720.
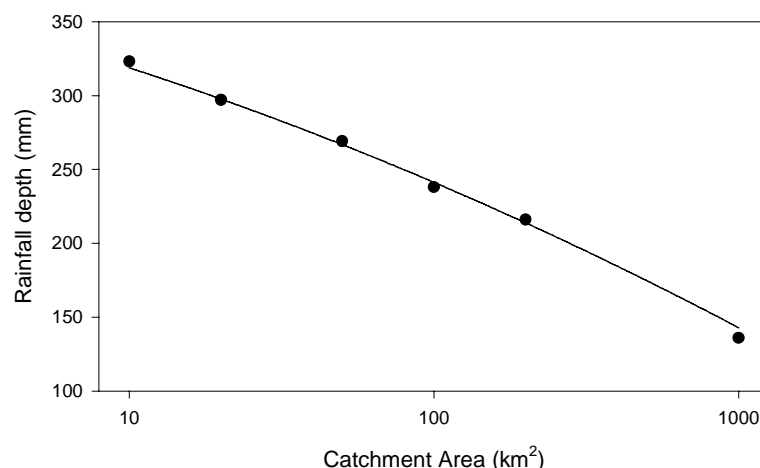
Figure 5.3.4 Rainfall depth versus catchment area from the centre of the storm for the most intense 5 hour period of the storm at Jabiru on 4 February 1980

The constituent concentrations that would occur in Swift Creek under this extreme dilution model are also presented in table 5.3.2. The Mg and SO_4 concentrations are still well below the concentration at which any biological impact could be expected to occur and the calculated increases are comparable with the naturally occurring concentrations of these chemicals in Swift Creek, about 0.4 and 0.3 mg/L for Mg and SO_4 respectively. The uranium concentration is intermediate between the safe and the effects concentrations for uranium. Hence, under this scenario adverse effects may occur in some species, particularly invertebrates, but effects on fish would not be expected. It is worth noting that the concentration in Swift Creek would only remain at the indicated value for a matter of hours. This period should be compared with the 6 day period of the toxicological test. In addition, the uranium concentration adopted for runoff from the ore stockpile is considered to be a worst case estimate and is higher than that estimated by ERA by a factor of about 10.

The conclusion of this analysis is that, under normal circumstances, no effect on aquatic animals living in Swift Creek downstream from the Jabiluka mine would be expected to occur even when the volume of excess water discharged is that with an exceedence probability of 1 in 50,000 over the life of the mine. If the discharge results from an extreme rainfall event with an exceedence probability much greater than 1 in 100 at the end of a wet season in which the rainfall has an exceedence probability of greater than 1 in 1000, some adverse effects may occur in invertebrates, but adverse effects on fish would not be expected. Any adverse effects on invertebrates would be very short-lived.

5.3.4 Risks associated with dam failure

The risk assessments carried out above refer to a contingency situation in which the accumulated runoff from the catchment of the water storage pond at Jabiluka exceeds the capacity of the pond. It has been assumed that contingency measures are in place to ensure that, in these circumstances, water from the TCZ is diverted and allowed to flow freely to Swift Creek. In this way, overtopping of the pond itself would be avoided and the structural stability of the pond would, therefore, not be threatened.

In this section, the risk to the environment associated with structural failure of the water storage pond is assessed. Such a failure could arise from overtopping of the pond if the above contingency procedures fail, static failure of the constructed embankment or the occurrence of a severe earthquake.

So far in this review, the water storage pond has been considered as a single entity with an area of 9 ha. This has been adequate for all issues considered previously. In reality, however, the water management system for the JMA – Original Concept included two ponds. Storm water runoff from the stockpiles, washdown, crushing plant and the mine would be contained in a 4 ha raw water pond. Better quality water running off from the mill area would be contained in a 5 ha containment pond. This water would be transferred to the raw water pond on demand. During extended periods of low rainfall, water would be transferred from the bore field to the raw water pond to maintain operation of the mill.

It has been pointed out in section 5.2.4 that pond evaporation will probably need to replace enhanced evaporation in the ventilation system, at least to a significant extent and that, to provide control of pond evaporation, the water retention pond could be partitioned into three or four compartments with connecting spill ways and a water pumping system. In these circumstances, the water quality in each compartment will be similar because of the exchanges of water between compartments. For this reason, the risk of structural failure of the pond will be based upon the assumption of a single pond.

Table 5.3.3 Estimates of the maximum concentrations of the principal constituents in the water retention pond at Jabiluka

Chemicals	Concentration mg/L	Radionuclides	Concentration Bq/L
Uranium	0.8	^{238}U	10
Magnesium	5	^{234}U	10
Sulphate	20	^{230}Th	0.03
		^{226}Ra	3.4
		^{210}Pb	.2
		^{210}Po	0.03

Water inputs to the pond will arise from direct rainfall on the pond area, runoff from the ore stockpile, runoff from other areas of the TCZ (most of which will produce good quality water) and water pumped from the mine. Water from the mine may contain concentrations of uranium and magnesium sulphate at higher than background values but, because this water will have been exposed mainly to inert material rather than ore, these concentrations will be very small compared to runoff from the ore stockpile. The concentrations of uranium, magnesium, sulphate and the long-lived radionuclides of the uranium series in the retention pond have, therefore been estimated on the basis of the concentrations in runoff from the ore stockpile divided by a dilution factor determined by the ratio of the total TCZ catchment to

that of the stockpile. This is considered conservative because it ignores the substantial input of relatively good quality water from the mine. The resulting estimates of the concentrations of the various constituents in the water retention pond are given in table 5.3.3.

Overtopping of the pond

The probability of the pond overtopping in the absence of contingency measures can be derived from figure 5.2.1 using a volume equal to the total volume of the pond including the freeboard volume. For a total depth of 9.5 m (PER p 4–52) the pond volume would be 855,000 m^3. From figure 5.2.1, the exceedence probability for this volume over the life of the mine is about 0.0005 or 5 in 10,000.

The radiological impact on people living downstream from the mine, and consuming traditional foods collected from downstream waterbodies, has been estimated following the procedures outlined in section 5.3.2. It was assumed that overtopping of the dam would, in the absence of an engineered spillway, lead to structural failure of the pond embankment and all of the water in the pond, 855,000 m^3, would be discharged to Swift Creek. The concentrations of radionuclides given in table 5.3.3 were multiplied by this water volume to obtain the loads of each nuclide and the dose conversion factors for the Ranger radiological assessment model from Martin et al (1998) were used to estimate the radiation dose for each radionuclide. These doses were added to obtain the overall dose estimate of 150 µSv. Thus, even for this catastrophic event, the expected dose received by members of the public would not be greater than 15% of the annual limit recommended by the International Commission on Radiological Protection.

The ecological impact in Swift Creek resulting from overtopping of the pond will depend considerably on the flow conditions in the creek at the time of dam failure and the time taken to drain the dam. Since such an event could only occur towards the end of a very exceptional Wet season, it would be expected that creek flow would be relatively high. However, assuming that the flow in the creek would be equal to the average Wet season flow (about 3.5 m^3/s, and that the time taken to drain the dam is 12 hours, the total volume of creek water in which the dam water would be diluted would be about 150,000 m^3 which is small compared to the volume of water in the pond. Hence, the concentrations of uranium, magnesium and sulphate in the creek during this time would be those given in table 5.3.3.

Both the Mg and SO$_4$ concentrations would, therefore, be lower than the concentration limits given in table 5.3.2 and, while greater than natural concentrations, would not be expected to cause significant impact on ecosystems. The uranium concentration in table 5.3.3 is higher than the Lowest Observed Effect Concentration for *hydra viridissima* given in table 5.3.2 and effects on some aquatic animals could, therefore be expected in Swift Creek. However, from the results of Bywater at al (1991) and Holdway (1992) effects on fish would not be expected.

In terms of broader ecological impact on the wetlands of Kakadu National Park, the water from the pond would be diluted in floodplain waters until concentrations of uranium become lower than 190 µg/L. During the Wet season, the depth of water on the floodplain is about 2 metres. Hence the maximum affected area of the floodplain for a discharge of 855,000 m^3 would be 1.8 km^2. Thus, in the case of overtopping the retention pond, there is a risk of about 5 in 10,000 that an area that is about 1% of the Magela floodplain would experience some adverse effects on aquatic animals. Fish and many other species would not be affected. Between about 2 km^2 and 20 km^2, adverse effects may persist but beyond 20 km^2 no effects should be observed. In addition, any effects will be transitory and the system would fully recover following flushing by the natural waters of the Magela Creek.

It should be noted that if a properly engineered spillway were installed in the wall of the retention pond, the dam would be protected from destruction under overtopping. This would result in the loss of much lower volumes of water over a longer period and would fully protect both Swift Creek and the Magela floodplain under the conditions considered here. It is recommended that such a spill-way be incorporated in the design of the retention pond.

Static failure of the retention pond structure

Static failure of the water retention pond could, in principle, occur as a result of piping (the erosive action of water passing through or under the dam wall) or slope failure (the downward and outward movement of a mass of soil beneath the dam wall) as a result of excessive pressures being applied.

Failure as a result of piping is not considered to be an issue with the specific design adopted by ERA because there is a double impermeable liner on the floor of the dam and on the inner walls. In addition, a seepage detection system has been included in the design so that, were the liner to be damaged, seepage would be detected at an early stage and repair action implemented.

The retention pond structure has been designed with a factor of safety (FS) of 1.7 against slope failure. This FS was calculated under circumstances in which the pond is at its full capacity with the liner intact. Hence, the probability of slope failure should be less than the probability of overtopping which was estimated above to be about 0.0005 or 5 in 10,000. Since slope failure would only arise under circumstances similar to those considered for overtopping, the estimates of environmental impact derived above for overtopping would also apply to slope failure.

Table 5.3.4 Variation return period with peak ground acceleration arising from an earthquake for a site near Darwin

Return Period (Years)	Peak Ground Acceleration mm/s^2
1	98
10	218
100	484
500	842
1000	1068
2000	1349
3000	1544
5000	1834

Failure due the occurrence of a severe earthquake

The factor of safety of 1.7 for the designed retention pond structure was derived by considering not only conditions that would lead to static failure but also ground level motions with an acceleration of 0.08 g arising from an earthquake, where *g* is the acceleration due to gravity. (The acceleration 0.08 g is that specified in the relevant Australian standard for normal structures.) The engineering consultant responsible for the design of the retention pond, Golder Associates, has advised the Supervising Scientist (private communication) that the acceleration corresponding to a safety factor of 1.0, at which dam failure could commence, is 0.39 g (3830 mm/s^2).

The Australian Geological Survey Organisation has recently completed a hazard analysis for normal structures (Kevin McCue, private communication) for a site near near Darwin and the results are listed in table 5.3.4. This site is tectonically similar to that at Jabiluka and the study can be used to provide an indicative ground hazard analysis for the Jabiluka site.

In the above study, only local and regional earthquakes were considered in the hazard analysis since the frequent but distant large earthquakes in the Banda Sea, Indonesia, are too far away to cause damaging ground motions for normal structures. They should be considered for a water retention pond since they give rise to many cycles of ground motion. It is recommended that ERA commissions such a study at the detailed design stage of the Jabiluka project.

The ground level acceleration which could lead to failure of the retention pond structure (3830 mm/s^2) is beyond the range of accelerations given in table 5.3.4 and the return period for this acceleration is considerably in excess of 5000 years. Extrapolation of the data in the table will be subject to uncertainties associated with the limitations of the underlying data set and model dependence arising from the attenuation relation used in the study. Nevertheless, accepting that such uncertainties are present, we have extraploated the above data (which are linear on a log-log plot) to obtain an estimated return period of 50,000 years for an earthquake that could cause failure of the retention pond structure. Thus, over the period of the mine life, the probability of structural failure would be approximately 0.0006 (0.06%). Rounding up, a probability of failure of 0.001 will be assumed in subsequent analysis.
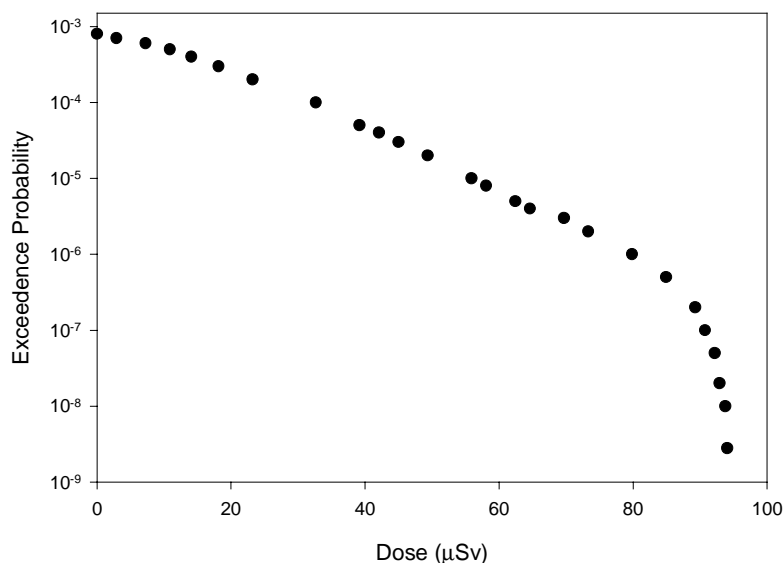
Figure 5.3.5 Probability versus radiation exposure of members of the public resulting from the discharge of water from the Jabiluka mine site as a result of an earthquake

An earthquake could clearly occur at any time of the year and during any year of the 30-year mine life. Thus one needs to know the probability that the volume of water contained within the pond will be exceeded on the specific day of the earthquake rather than the probability that this volume will be exceeded on <u>any</u> day during the 30 year life of the mine. Chiew and Wang (1999) derived the daily exceedence probability by running the Monte Carlo simulation of the water management system for more than 350,000 days. The variation of exceedence probability with volume was converted to exceedence probability as a function of radiation exposure using the procedures outlined in section 5.3.2 and the concentration data

in table 5.3.3 and by multiplying the exceedence probability values by the risk of occurrence of an earthquake. The results are presented in figure 5.3.5.

From these data it can be seen that the risk of radiation exposure of members of the public would be extremely low. At the 1 in 10,000 level of probability, the estimated radiation exposure is about 30 μSv. The highest calculated exposure, which is less than one tenth of the internationally accepted limit, has an extremely small exceedence probability.

For an earthquake that occurs in the Wet season, the probable maximum area of the Magela floodplain within which any ecological impact would be expected to occur can be calculated as outlined above for the case of overtopping of the dam. The exceedence probability versus affected area is shown in figure 5.3.6. Also shown is the area beyond which one can be confident no effects will occur.
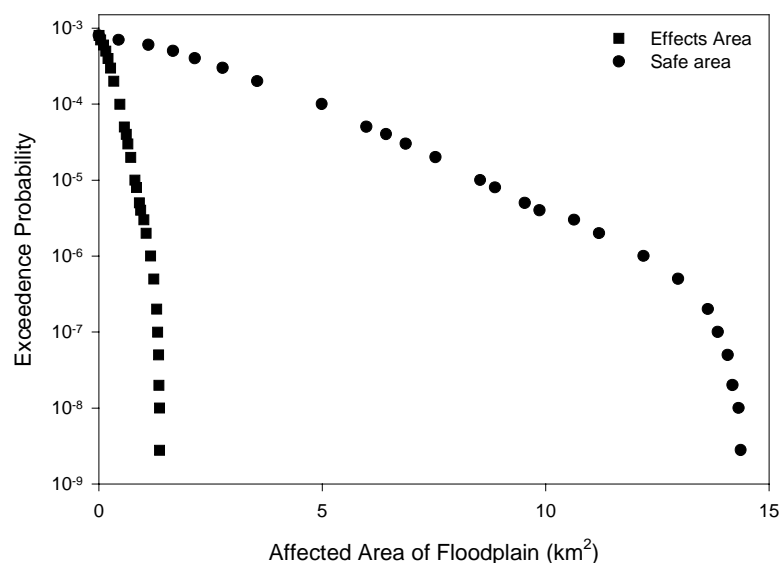
Figure 5.3.6 Probability versus the affected area of the Magela floodplain for a severe earthquake. Beyond the safe area, no adverse effects are expected. Adverse effects on invertebrates are expected inside the effects area. Between the two areas, some residual effects may occur.

Hence the maximum area that should be affected is about 1.5 km^2 but the probability of this occurring is extremely small. The area affected at the 1 in 10,000 level of probability is less than 0.5 km^2 which is less than 0.3% of the floodplain area. At the same level of probability, residual effects may occur for some species of invertebrates out to an area of about 5 km^2. Even within these areas the impact would be very small (for example, fish should not be affected) and the system would fully recover following flushing by the natural waters of the Magela system.

If an earthquake occurred in the Dry season, the depth of water in the Magela floodplain would be less than that assumed above and the area of impact would be greater. Nevertheless, the probability of an impact remains small and the system would recover during the following Wet season.

5.3.5 Contingency measures

ERA has described in the EIS, the Supplement to the EIS and in the PER contingency procedures that would be adopted in the case of extreme events occurring that affect the

water management system at Jabiluka including, in a worst case scenario where no other acceptable alternative exists, the pumping of water to the mine void. The analysis presented in this chapter suggests that contingency planning should include the measures discussed below.

Rainfall runoff from the ore stockpile represents about 1.5% of the runoff from the remainder of the Total Containment Zone for the Jabiluka Mill Alternative. The water quality of runoff from the stockpile will, however, be much poorer than that from the remainder of the catchment. Hence, in the extreme scenario envisaged in sections 5.3.2 and 5.3.3 where there is a 1 in 50,000 probability that about 200,000 m^3 would be discharged from the TCZ to Swift Creek, the volume of poor quality water from the ore stockpile would only be 3000 m^3. This volume could easily be accommodated in the freeboard volume of the water retention pond without downgrading the freeboard capacity significantly. It is, therefore, recommended that runoff from the ore stockpile should be isolated from runoff from the remainder of the TCZ so that it is always directed to the pond while, under extreme conditions, runoff from the rest of the TCZ is diverted away from the storage pond. This measure would reduce still further the risk associated with exceeding the capacity of the storage pond.

The assessment of the risks associated with overtopping of the water retention pond was based upon the assumption that overtopping would lead to structural failure of the pond embankment and that all of the water in the pond, 855,000 m^3, would be discharged to Swift Creek. If the pond were constructed with a properly designed spillway, this would ensure that, even if diversion contingency measures fail, the pond structure would not fail when the overtopping height is reached. This would reduce substantially the impact arising in the event of overtopping because only a small volume of water would be released to the environment rather than the full volume of the pond. It would also, as a by-product, mean that the operation of the mine could continue even following such an extreme event without the need to rebuild the dam.

5.6 Summary of findings on the storage of uranium on the surface

Modelling of the water management system at Jabiluka under current climatic conditions

- This review has included hydrological modelling of the water management system at Jabiluka using a stochastic daily water balance model which incorporates the recommendations of this review on the appropriate rainfall record and evaporation, a realistic distribution of evaporative losses in the ventilation system throughout the year, and a simple soil water capacity model for runoff. The system modelled was the Jabiluka Mill Alternative – Original Concept but with tailings returned to the mine void rather than in tailings ponds at the surface.

- The model has enabled estimates to be made of the storage capacity required as a function of exceedence probability over the 30-year mine life under current climatic conditions.

- The probability that the pond volume proposed by ERA in the PER (810,000 m^3) would be exceeded over the life of the mine is about 1 in 1000. The pond volume required to achieve an exceedence probability of 1 in 10,000 over the life of the mine would be about 940,000 m^3.

Review of the hydrological model adopted by ERA

- The Supervising Scientist has reviewed the hydrological model adopted by ERA in the design of the water management system at Jabiluka. This review has resulted in a number of recommendations for improvement of the model.

- The effect on the volume of the water storage pond arising from the adoption of these recommendations is as follows:

  - The inclusion of interannual variability in evaporation and the inverse relationship between rainfall and evaporation leads to an increase in the required pond volume of about 3%.

  - The use of a simulated distribution of monthly rainfall rather than distributing annual rainfall to each month in fixed proportions determined from a typical distribution leads to an increase in the required capacity by about 1.7%.

  - The use of a more realistic distribution of ventilation system losses between the Wet and Dry seasons rather than a constant value for each month leads to an increase in the required capacity by about 1.2%.

  - The use of pan factors recommended in this review rather than those used by ERA in the PER results in an increase in the required volume of about 2.5%.

  - The use of a daily water balance model rather than a monthly model leads to an increase in required pond volume of about 1.4%.

  - The use of conceptual rainfall-runoff model rather than fixed runoff coefficients leads to a decrease in the required pond volume of about 0.4%.

- The combined effect of adopting the recommendations of this review on each of the above topics rather than the model used by ERA is that the pond volume required to achieve a given exceedence probability will increase by about 10%.

Use of pond evaporation rather than enhanced evaporation in the ventilation system

- The use of pond evaporation rather than enhanced evaporation in the ventilation system would lead to a reduction in the required storage capacity of about 30% because the full evaporative capacity would be available from the commencement of operations rather than achieving its maximum effect only after 10 years of operation.

- It is recommended that ERA, in its detailed design of the Jabiluka water management system, uses increased pond evaporation rather than enhanced evaporation in the ventilation system. In making this recommendation, it is recognised that some enhanced evaporation in the ventilation system as a result of dust suppression procedures is inevitable. This will need to be modelled carefully by ERA to achieve the optimum water management system.

- Partitioning the water retention pond into three or four compartments with connecting spill ways and a water pumping system is one way in which control of evaporative losses could be achieved. Evaporative losses in dry spells could be minimised by pumping all remaining water into one of the compartments and could be maximised in wetter periods by using the full evaporative capacity of all of the compartments. It is recommended that ERA consider this approach in the detailed design of the water management system at Jabiluka.

Effect of climate change on the required storage capacity

- The minimum predicted temperature increase is the extreme scenario for water balance modelling since this would minimise evaporation and hence maximise the required storage volume. The minimum predicted increase of 0.35ºC over the next 30 years is insufficient to have any significant impact on evaporation. There is no need, therefore, to adjust the hydrological model to take the effect of temperature change into account.

- The maximum predicted change in annual rainfall from global warming over the next 30 years is 1%. There is, therefore no need to repeat the simulation of the water management system to take this effect into account. The effect of climate change will be negligible.

- The effect of the predicted increase in storm intensity due to global warming has been assessed using the results of a sensitivity analysis. The results indicate that this increase in storm intensity would not have any significant impact on the required storage capacity of the water management system at Jabiluka.

Risk assessment of the ERA proposal

- A risk assessment has been carried out for the water management system proposed by ERA for the Jabiluka mine. In this context, it is important to note that tailings will not be stored at the surface. The principle hazard that needs to be assessed is the possible impact on people and on downstream ecosystems arising from the unplanned discharge of water that has been in contact with uranium ore.

- In conducting the risk assessment, estimates have been made of the concentraions of solutes in runoff from the ore stockpile. All of these concentrations are considered to be maximum expected values and some are likely to be significant over-estimates.

- The risk assessment included a contingency situation in which the accumulated runoff from the catchment of the water storage pond at Jabiluka exceeds the capacity of the pond and the excess water from the Total Containment Zone is diverted and allowed to flow freely to Swift Creek. Also assessed is the risk to the environment associated with structural failure of the water storage pond arising from overtopping of the pond, static failure of the constructed embankment, or the occurrence of a severe earthquake.

Risks associated with exceeding the available water storage capacity

- Estimates have been made of radiation exposure of members of the public resulting from an exceptional Wet season in which the storage capacity of the water retention pond is exceeded and the excess water is discharged to Swift Creek. The probability that any member of the public would receive a radiation dose of 20 µSv on one occasion during the 30 year life of the mine would be less than 1 in 10,000. The annual dose limit recommended by the International Commission on Radiological Protection for members of the public is 1000 µSv per annum. The conclusion is, therefore, that the water management system proposed by ERA for Jabiluka is one that poses an insignificant radiological risk to people living in the vicinity of the mine and consuming traditional foods obtained from the waterbodies downstream from the mine.

- Estimates have also been made of probable effects on aquatic animals resulting from an exceptional Wet season in which the storage capacity of the water retention pond is exceeded and the excess water is discharged to Swift Creek. The assessment included both radiological and chemical exposure. The conclusion reached is that, under normal circumstances, no effect on aquatic animals living in Swift Creek downstream from the Jabiluka mine would be expected to occur even when the volume of excess water

discharged is that with an exceedence probability of 1 in 50,000 over the life of the mine. If the discharge results from an extreme rainfall event with an exceedence probability much greater than 1 in 100 at the end of a Wet season in which the rainfall has an exceedence probability of greater than 1 in 1000, some adverse effects may occur in invertebrates, but adverse effects on fish would not be expected. Any adverse effects on invertebrates would be very short-lived.

Risks associated with overtopping the water storage pond

- The probability of the pond overtopping in the absence of contingency measures has been estimated to be 5 in 10,000. It was assumed that overtopping would lead to complete structural failure of the pond embankment. The estimated radiation exposure of members of the public arising from such an event is about 150 µSv. Thus, even for this catastrophic event, the expected dose received by members of the public would not be greater than 15% of the annual limit recommended by the International Commission on Radiological Protection.

- The uranium concentration in Swift Creek following overtopping of the retention pond and subsequent total failure of the dam walls would be expected to give rise to adverse effects on some aquatic invertebrates in the Creek but adverse effects on fish would not be expected.

- There is a risk of about 5 in 10,000 that, following overtopping of the water retention pond, an area that is about 1% of the Magela floodplain would experience some adverse effects on aquatic animals. Fish and many other species would not be affected. Between about 2 km² and 20 km², adverse effects may persist but beyond 20km² no effects should be observed. In addition, any effects will be transitory and the system would fully recover following flushing by the natural waters of the Magela Creek.

- If a properly engineered spillway were installed in the wall of the retention pond, the dam would be protected from destruction under overtopping. This would result in the loss of much lower volumes of water over a longer period and would fully protect both Swift Creek and the Magela floodplain under the conditions considered here. It is recommended that such a spill-way be incorporated in the design of the retention pond.

Risks associated with slope failure of the embankment of the water storage pond

- The probability of slope failure is estimated to be less than the probability of overtopping which was estimated above to be about 5 in 10,000. Since slope failure would only arise under circumstances similar to those considered for overtopping, the estimates of environmental impact derived above for overtopping would also apply to slope failure.

Risks associated with a severe earthquake

- Over the period of the mine life, the probability of structural failure of the water retention pond arising from a severe earthquake has been estimated to be approximately 5 in 10,000. In deriving this estimate, only local and regional earthquakes were considered. The frequent but distant large earthquakes in the Banda Sea, Indonesia, should be considered in the design of a water retention pond since they give rise to many cycles of ground motion. It is recommended that ERA commissions such a study at the detailed design stage of the Jabiluka project.

- The risk of radiation exposure of members of the public resulting from such an earthquake would be extremely low. At the 1 in 10,000 level of probability, the estimated radiation exposure is about 30 µSv. The highest calculated exposure, which is less than

one tenth of the internationally accepted limit, has an extremely small exceedence probability.

- For an earthquake that occurs in the Wet season, the maximum area of the Magela floodplain in which adverse effects on some aquatic invertebrates might be expected is about 1.5 km^2 but the probability of this occurring is extremely small. The area affected at the 1 in 10,000 level of probability is less than 0.5 km^2 which is less than 0.3% of the floodplain area.. At the same level of probability, residual effects may occur for some species of invertebrates out to an area of about 5 km^2. Even within these areas, the impact would be very small (for example, fish should not be affected) and the system would fully recover following flushing by the natural waters of the Magela system.

- If an earthquake occurs in the Dry season, the area of impact would be greater. Nevertheless, the probability of such effects occurring remains very low and the system would recover during the following Wet season.

Contingency measures

- It is recommended that runoff from the ore stockpile should be isolated from runoff from the remainder of the Total Containment Zone so that it is always directed to the water retention pond while, under extreme conditions, runoff from the rest of the TCZ is diverted away from the storage pond. This measure would reduce still further the risk associated with exceeding the capacity of the storage pond.

- It is recommended that the water retention pond be constructed with a properly engineered spillway to ensure that, even if diversion contingency measures fail, the pond structure would not fail when the overtopping height is reached. This would reduce substantially the impact arising in the event of overtopping because only a small volume of water would be released to the environment rather than the full volume of the pond.

6 Long-term storage of mine tailings

6.1 Introduction

In this chapter, issues related to the storage of tailings at the Jabiluka mine will be addressed. Since there have been a number of proposals for the storage of tailings, it is appropriate to clarify at the outset what the current proposal is.

When ERA submitted the EIS on Jabiluka, the main thrust of the proposal was the Ranger Mill Alternative under which, as stated earlier in this report, all tailings produced from the milling of the Jabiluka ore would be deposited in the mined-out pits at Ranger. In the EIS, ERA also identified its original concept for the Jabiluka Mill Alternative. The intention at that stage was that, if milling at Jabiluka was the only option available to the company, about 75% of the tailings would be returned as a cemented paste to the undergound mine void and the remaining 25% of the tailings would be stored in a large tailings dam (total area about 55 ha) constructed on the land surface at Jabiluka. The intention was to rehabilitate the tailings dam *in situ* at the end of mining.

The original JMA concept did not receive Government approval during the EIS process. By the time ERA submitted the Public Environment Report on the Jabiluka Mill Alternative, it had developed a different approach to tailings management. Under the revised plan, special pits would be excavated in the Kombolgie sandstone near the mill at Jabiluka and these would enable all tailings to be placed below ground from the outset and the site rehabilitation plan would include capping of the tailings pits with waste rock and final revegetation of the landform.

This revised proposal was not accepted by the Commonwealth Government when it granted approval for the Jabiluka Mill Alternative to proceed. Rather, the Government required ERA to place all tailings in the mine void and in specially excavated stopes or silos in the vicinity of the orebody. ERA was required to prepare an amended proposal to the satisfaction of the Supervising Scientist and the Supervising Authorities prior to the granting of a licence for the export of uranium from the Jabiluka site.

This amended proposal has not yet been received from ERA but detailed planning is underway. ERA has cooperated with the Supervising Scientist in the preparation of this review by providing information on its current plans, thus enabling the Supervising Scientist to assess the environmental impact that might arise.

The proposal that is assessed in this chapter refers to the placement of 100% of the tailings from the processing of Jabiluka ore in the mine void and specially excavated silos in the vicinity of the mine void. The environmental issues that require assessment are twofold:

(i) containment of the solid tailings so that they do not represent a long-term threat to the wetlands of Kakadu, and

(ii) leaching of contaminants from the tailings, dispersion of the solutes in groundwater and the consequent potential impact on the wetlands of Kakadu.

These issues are considered in the next two sub-sections.

6.2 Erosion of tailings in the long-term

The location of the mine void and the approximate location of the tailings silos as currently planned by ERA are shown in figure 6.3.3 The highest part of the mine void is about 80 m

below mean sea level and about 100 m below the land suface in Mine Valley. The highest point of the tailings silos (as currently planned by ERA) is about 40 m below sea level and about 110 m below the land surface of the crest between Mine Valley and the location of the mine portal and surface facilities at Jabiluka.

Thus, once the mine is backfilled and sealed following completion of mining at Jabiluka, the only mechanism for physical dispersal of the tailings solids will be erosion of the overlying bedrock. Clearly, the whole land mass would need to be eroded away and by that time the wetlands of Kakadu would no longer exist. Physical dispersal of the tailings does not, therefore, pose a threat to the wetlands of Kakadu.

Geologic denudation rates in the Alligator Rivers Region have been summarised by the Supervising Scientist (Cull et al 1992). The mean and standard deviation of 45 measurements were 0.04±0.03 mm per annum. These data included a number of measurements made in the vicinity of the Jabiluka No 1 orebody so that they are directly applicable to the current assessment. These data are consistent with other measurements in the region. For example, Williams (1973 and 1976) recorded denudation rates between 0.011 and 0.054 mm per annum.

Following extraction of uranium in the mill, the tailings will contain uranium at concentrations about 5% of the original concentration in the ore, but all of the radioactive progeny will be present at approximately their original ore concentrations. Assuming that erosion rates will be similar in the future and using the mean denudation rate of 0.04 mm per annum, the time required to erode the bedrock overlying the tailings in the mine void and the silos would be about 2 million years. This time scale is about 25 times the radioactive half-life of ^{230}Th, the longest lived radioactive product of uranium. Hence the excess concentrations of all the radioactive progeny will have decayed away by the time the tailings are exposed and they will be in equilibrium with the residual uranium. This residual uranium concentration is about 30 times greater than the average concentration of uranium in the rocks of the Alligator Rivers Region but clearly any tailings dispersed from the site in the very long term would be mixed with, and diluted by, very large quantities of inert material from the surrounding bedrock. Thus, dispersal of tailings in the very long term will not constitute a hazard for future generations.

6.3 Leaching of contaminants from tailings

6.3.1 Hydrogeological description of the area

A detailed study of the hydrogeology of the Jabiluka area and modelling of groundwater contaminant dispersion has been carried out by Kalf and Dudgeon (1999) (Attachment E) as part of this review.

Groundwater flow in the vicinity of the mine is topographically controlled. A relatively high mean annual rainfall of about 1500 mm, which occurs mainly in the annual Wet seasons, and relatively low permeability of the sandstone hills surrounding the mine site maintain high water table levels in the hills. Both surface water and groundwater drainage is from the hills towards the major valleys which run approximately east and west from the surface water divide which is located near the mine site. Groundwater flow in both of these directions eventually reaches the Magela floodplain in Kakadu National Park (see fig 6.3.1). The westward flow towards the floodplain follows the general line of Mine Valley. The eastward flow must turn north to follow the course of Swift Creek and flow further before it can reach the floodplain.
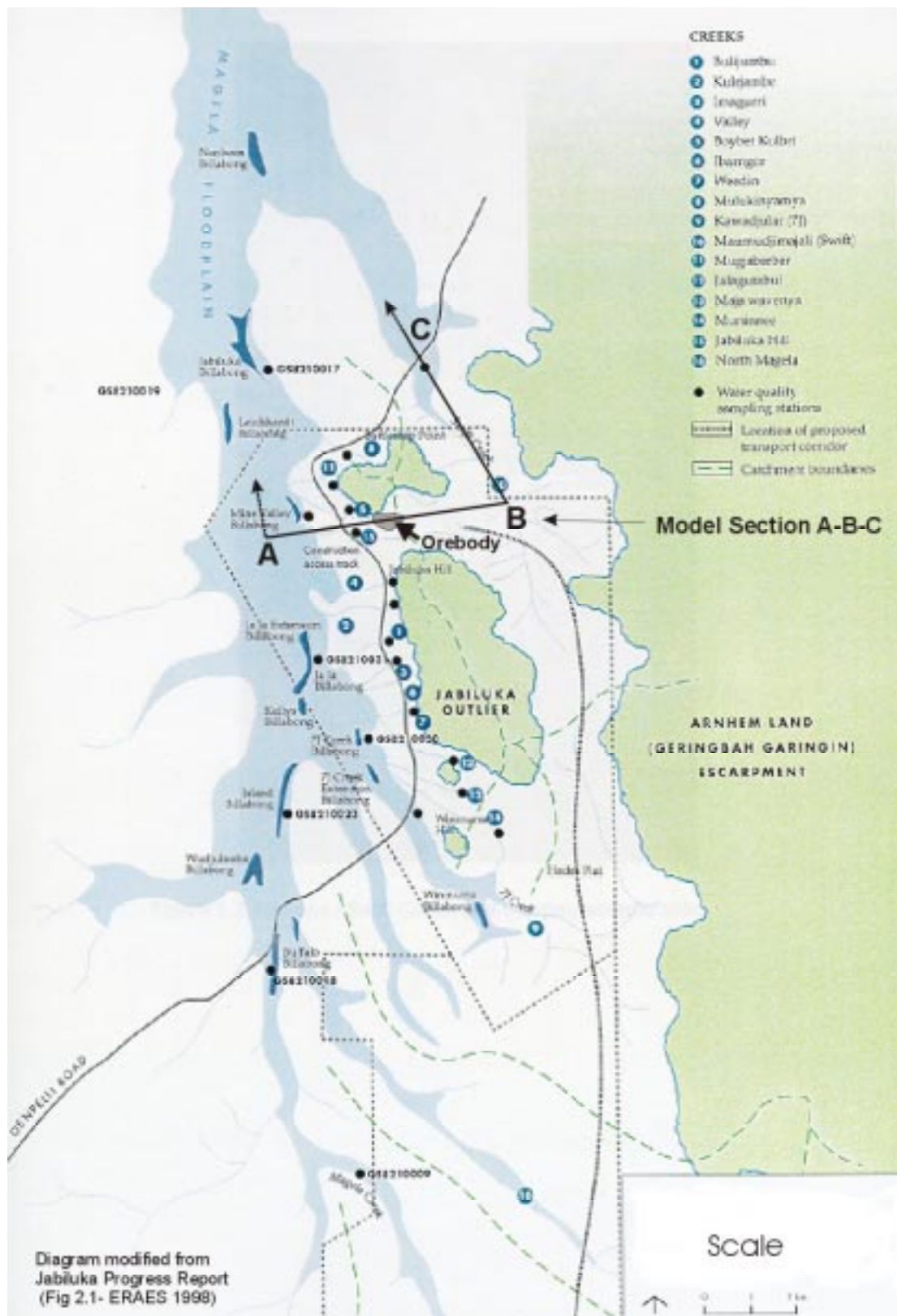
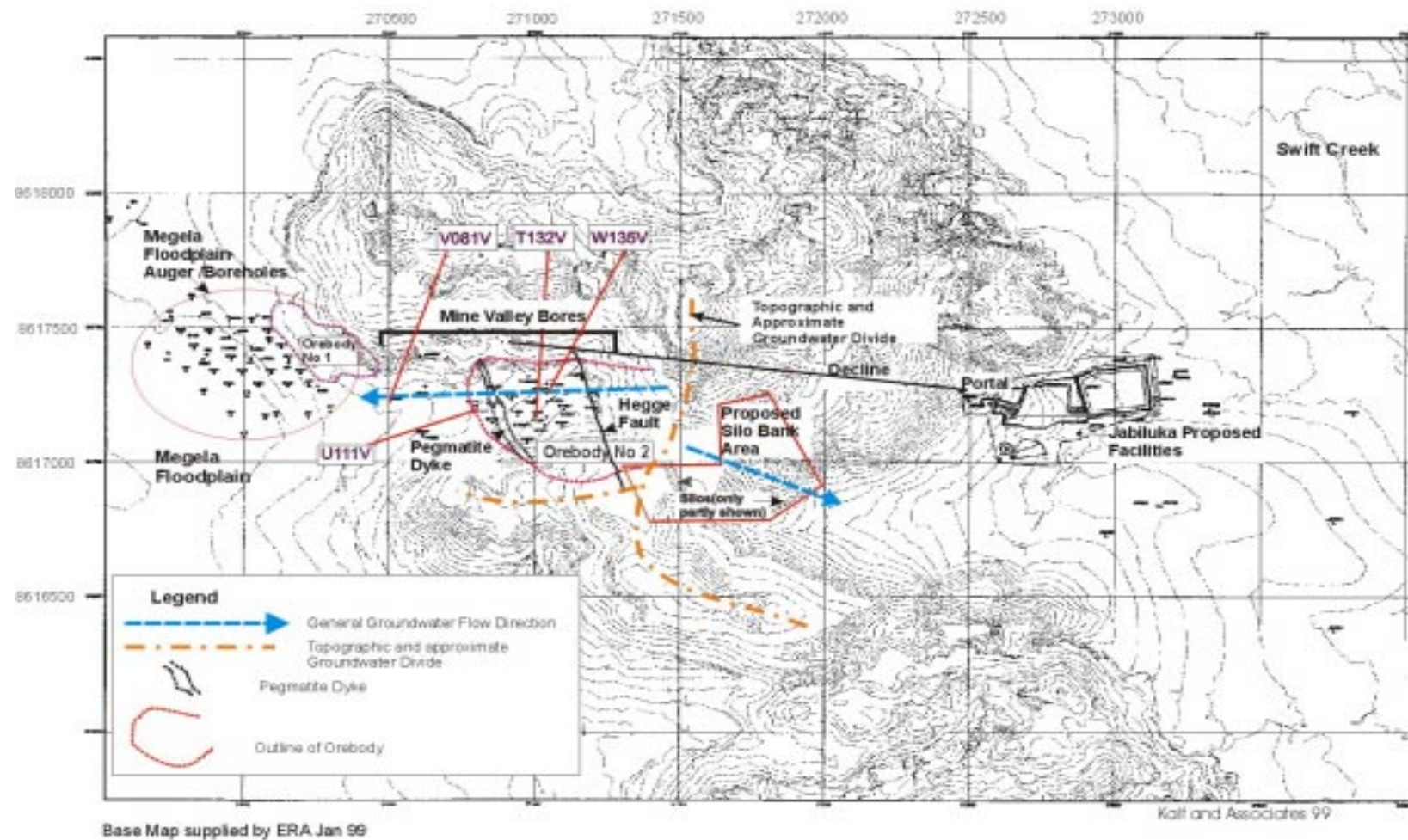**Figure 6.3.1** Hydrology and site features around Jabiluka

Figure 6.3.2 Topography and key hydrogeological features of the Jabiluka area

The Jabiluka orebody No 2 to be mined is contained within the Cahill Formation which is mostly schist although it 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 sandstone (see fig 6.3.3).

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 mainly grey and organic clays, 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 ore-body (fig 6.3.2). The pegmatite dyke has not been assigned any special properties for the modelling work undertaken, which is a conservative assumption because there is some indication that it may retard flow.

A hydrogeological section based on that given by Milnes et al (1998) is shown in figure 6.3.3. The orientation and extent of this section is shown in figure 6.3.1 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. Tailings derived contaminants were modelled by Kalf and Dudgeon (1999) along this section.

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.

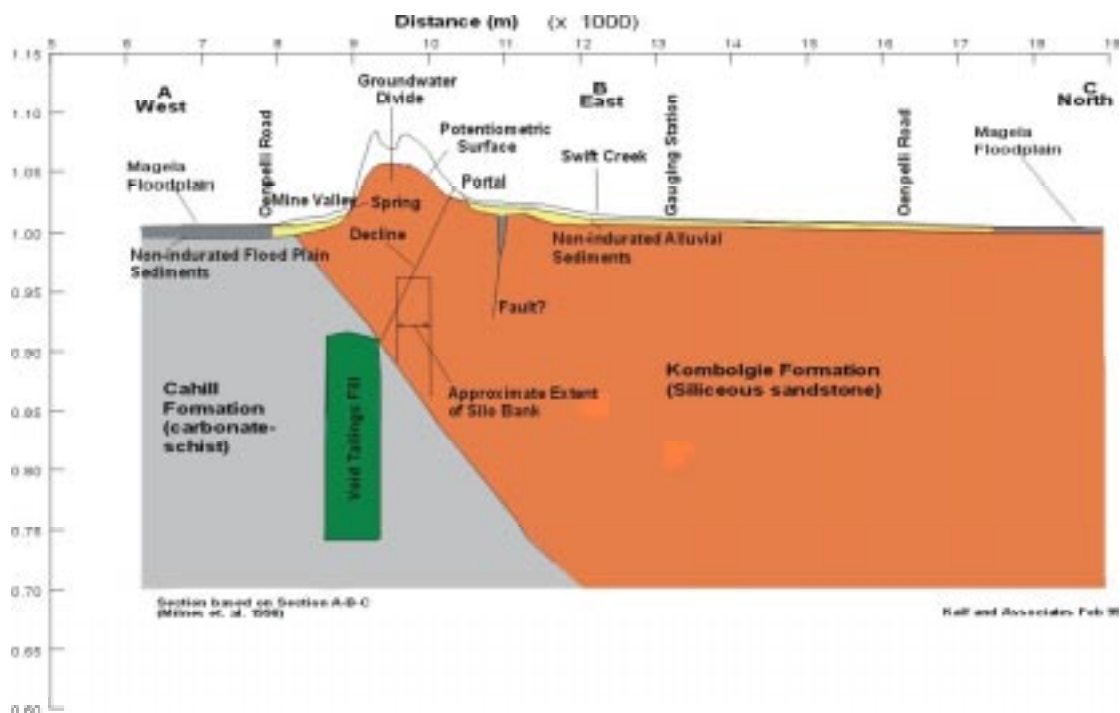- Floodplain non-indurated sediments.

Figure 6.3.3 Model section A-B-C, hydrological units, surface and sub-surface features near Jabiluka

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). 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 quartz sandstone over most of the area and schists and carbonates of the Cahill Formation further west.

The Magela floodplain sediments consist largely of grey and organic clays and silts, with prior stream channel deposits of sand and silt.

The permeability of the sandstone/schist has been estimated by Foley in ERAES (1998) to be in the range 0.017 to 0.1 m/day in Mine Valley, whereas further west the permeability of the shallow carbonate/schist has been reported at 0.08 to 0.2 m/day. East of the groundwater divide AGC-Woodward Clyde (1993) reported only very low flows above the sandstone schist contact and ERAES (1998) reported permeabilities in the range 0.001 to 1.2 m/day between the divide and Swift Creek, and 3×10^{-2} to 3×10^{-4} m/day in the Kombolgie Sandstone in this area. Kalf and Dudgeon (1999) conclude that the tailings silos should be excavated in the lower permeability Kombolgie sandstone east of the orebody, as is currently planned by ERA. This choice of location will minimise potential environmental impacts.

Analysis of waters within the groundwater system indicates that soluble salt concentrations in shallow groundwater near the orebody are in the range 620–680 μS/cm, with pH between 7.1 and 7.6. Chloride concentrations were between 6 and 20 mg/L, sulphate less than 14 mg/L, bicarbonate 50–223 mg/L and silica 5–12 mg/L (Deutscher et al 1980). Groundwater salinity to the east of the divide is low over a range of measured depths with reported values between

17 and 350 μS/cm (ERAES 1998). This range of values is supported by other measurements (as listed in ERAES 1998).

The groundwaters in the vicinity of the orebody, both to the west in Mine Valley and to the east towards Swift Creek, are in stark contrast to the groundwater underlying the Magela floodplain, which is of high salinity, is acidic, and has high sulphate concentrations. Pyritic layers in the estuarine sediments underlying the plain are extensively oxidised to form acid sulphate soils (East et al 1992) as a result of seasonal wetting and drying cycles. The soils on the floodplain are dominated by grey clays (East et al 1992). The chemistry of the groundwaters is consistent with these conditions. Deutscher et al (1980) reported sulphate concentrations of between 1500 and 6854 mg/L, accompanied by low pH (3 to 4) and high concentrations of Fe2+ (200–700 mg/L) where sulphate concentrations were high. The location of tested bores is given in figure 6.3.2. An interesting feature of the groundwater underlying the Magela floodplain is the low concentrations of radionuclides present with uranium exceeding 1 μg/L (125 mBq/L) in only two of forty seven samples collected by Deutscher et al (1980).

6.3.2 Description of the solute transport modelling

A hybrid modelling approach has been used in this review (Kalf & Dudgeon 1999) to model the fractured rock aquifer in the project area. The modelling incorporated the three main processes that control the movement of solutes in groundwater, viz advection, dispersion and retardation. Retardation is the term given to describe the collective processes of adsorption, precipitation/dissolution and other complex ion exchange reactions. A full description of the modelling and a list of the assumptions used in the approach are given by Kalf and Dudgeon (1999). The models used were:

- A two dimensional section finite element model (SEEP/W) of section A-B-C (see fig 6.3.1) to determine flow directions, head distributions and the range of Darcy velocities along the section.

- A three dimensional numerical solute transport model (MODFLOW-SURFACT) applied to determine the concentrations of solutes leached from the tailings paste material for use as the source concentrations in the analytical model.

- An analytical contaminant transport model to determine concentrations due to advection, dispersion in three co-ordinate directions and retardation. This model used as input the range of velocities and source concentrations determined from the first two models. This model was combined with Monte Carlo calculations to determine concentration profiles for a large number of different parameter values within selected ranges.

The three models above were used to predict downstream effects of the solutes stored in the Jabiluka tailings as follows. Firstly, the assumed steady state water heads were computed by the finite element model SEEP. The water surface from the model was fitted to approximate the measured water surface at Jabiluka. These heads were used to drive the contaminant transport through the three dimensional model MODFLOW-SURFACT to produce the 'source' groundwater solute concentrations at a nominal 2 m downstream from the silos. The three dimensional model is necessary because of the complexity of the tailings storage geometry. These 'source' concentrations, along with groundwater velocities from SEEP, were then used as input to the analytical model to compute solute concentrations further downstream. Use of the analytical model enables a large range of solutions to be derived for different model parameters, and in this way the sensitivity of the model predictions to a range of inputs can be assessed through Monte Carlo simulations. The hybrid model was run for the

equivalent of 1000 years for predictions of the movement of radium and uranium, and 200 years for other contaminants.

The hybrid approach utilised by Kalf and Dudgeon (1999) enables detailed calculations to be undertaken where necessary, without hindering the development of the large number of solutions required to undertake a proper risk assessment. The prediction of solute concentrations downstream of the tailings repositories at Jabiluka is not trivial because groundwater flow and contaminant transport are complex three-dimensional processes. It is not uncommon in studies involving groundwater modelling for the precision of the outcomes to be limited by availability of data, because of the high cost of obtaining appropriate data through drilling. At Jabiluka, ERA has had additional difficulties to overcome because of restrictions on access to areas from which data are required. The Monte-Carlo simulations help overcome these limitations by assessing model outputs for a wide range of parameters. The Monte-Carlo simulation requires a probability distribution of the range for each parameter, and, in the current work, each value of a particular parameter was assigned an equal probability; this approach is conservative and ensures *worst case* scenarios are produced.

Downstream concentrations of contaminants emanating from the tailings have been presented by Kalf and Dudgeon (1999) in dimensionless or normalised form so that they can be used for predicting the impact for a range of source concentrations. Relative or normalized concentrations are expressed in terms of fractions or percentages of the source concentrations whatever they may happen to be. The results in the modelling report can, therefore, be used to determine absolute concentrations once the source concentrations are known more precisely. For example, differing assumptions on the permeability of the tailings give rise to different effective 'source' concentrations two metres out from the mine void or silos. The effect of permeability on concentrations of solutes far from the source can then be assessed quite rapidly using the relative concentration data from the analytical model.

6.3.3 Properties and constituents of tailings

Recent developments in dewatering technologies (eg cyclones, centrifuges, belt filters etc) have enabled production of tailings 'pastes' which have a lower water content than the parent tailings material, and superior environmental performance. Addition of binders such as Portland cement, as is proposed at Jabiluka, can then be conveniently undertaken to ensure the tailings remain environmentally benign. Cincilla et al (1997) have suggested that the tailings stream should contain at least 15% by weight of particles of less than 20 μm diameter, and that under these circumstances segregation can be avoided in a tailings paste. Golder and Associates (1997) undertook measurements on the particle size distribution and rheological characteristics of tailings from Jabiluka; they found that greater that 30% of the tailings had a particle size less than 20 μm, and that the tailings were well suited to the application of paste technology.

Although only limited work has been completed on the properties of Jabiluka tailings because the mine is not operational, physical properties of tailings at Ranger have been studied by Richards et al (1990). Ore at Jabiluka and Ranger originates from Cahill Formation schists and will be subject to the same milling process. Hence the tailings from the two mines are expected to have similar physical and chemical properties. The tailings permeability is illustrated in figure 6.3.4 as a function of effective stress, because when tailings are in place they are subjected to overburden pressure that reduces their permeability. Richards et al (1990) fitted Equation 6.1 to the tailings permeability data, and their equation has been shown to be consistent with tailings permeability data at other minesites (B

Richards, pers comm). Although Richards et al (1990) suggest that the data illustrated in figure 6.3.4 are the most representative of their measurements on Ranger tailings, they also measured higher values of permeability, particularly in areas where significant segregation had occurred. This indicates that care will be needed in the management and placement of tailings into the repositories at Jabiluka.

Richards et al (1990) derived the following equation to represent the relationship between tailings permeability, k (m/s), and effective stress, h (KPa):

$$k = (3.0x10^{-7})/(10.72h^{2.14}) + 1.2x10^{-11} \qquad (6.1)$$

This equation has been plotted in figure 6.3.4. In the modelling work undertaken by Kalf and Dudgeon (1999) a tailings permeability of less than 10^{-4} m/day (approximately 10^{-9} m/sec) is recommended. The effective stress that would be required to achieve a permeability of 10^{-9} m/s can be calculated from Eq. 6.1, as 14 kPa. If approximate values are assumed for the tailings density of 2, and the density of water assumed to be 1, then 14 kPa of overburden stress can be achieved through a tailings overburden depth of approximately 1.4 m. For a 135 m deep silo at Jabiluka, 99% of uncemented tailings placed in a silo would have a permeability less than 10^{-9} m/s, and the mean tailings permeability in the 135 m high silo would be much less than 10^{-9} m/s (fig 6.3.4). The addition of 4% cement to the tailings can lower its permeability by a further three orders of magnitude. In addition to the effect of adding cement, the reduction in water content that will be achieved through dewatering the tailings (dewatering will be undertaken before cement additions) will improve the cohesiveness of the tailings and reduce the possibility of segregation, which can increase the permeability.
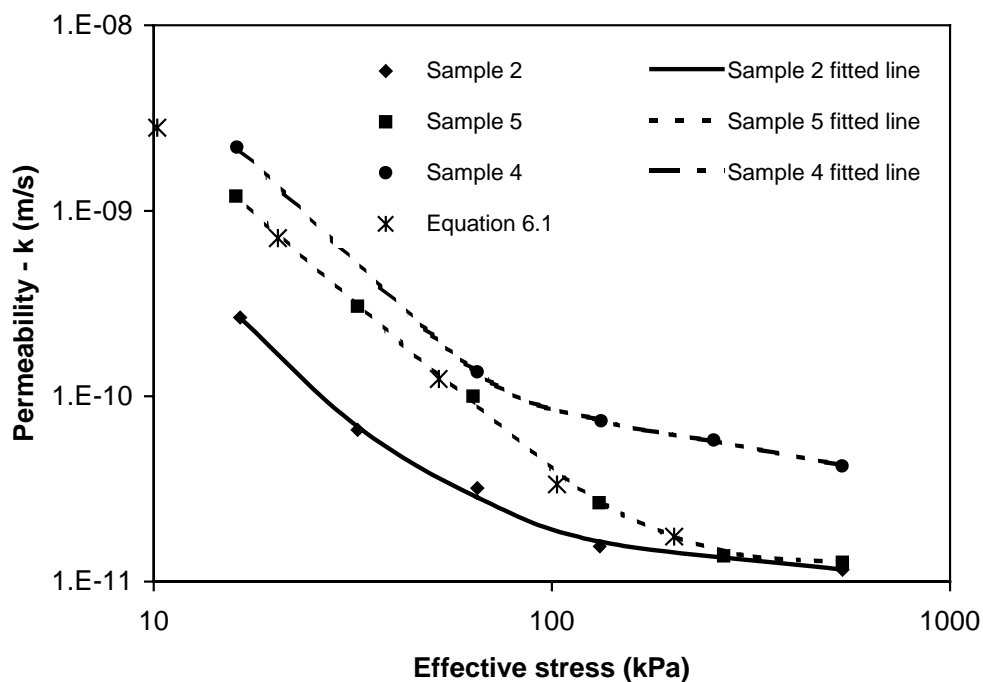

Figure 6.3.4 Permeability (m/s) as a function of effective stress (kPa) for tailings from the Ranger Mine located 22 km from Jabiluka

The considerations above indicate that a cemented tailings permeability of well below 10^{-9} m/s should be readily achieved at Jabiluka. The final percentage of cement to be added to the

tailings, and other procedures constituting the tailings treatment, are the subject of a current research program being undertaken by the mining company. The final fully developed tailings management procedure will be approved only after the Supervising Scientist is satisfied as to its efficacy.

The primary solutes of environmental concern in the tailings at Jabiluka are magnesium, sulphate, manganese, uranium, and radium. Some of the properties of these elements, which are needed to predict downstream concentrations are listed below in table 6.3.1. It is well known that the availability of metals in solution is a function of pH, with metal solubility generally decreasing with increases in pH. The addition of cement to the tailings paste will increase the pH, and a pH of up to 10 could be expected in Jabiluka cemented tailings. Also, it could be expected that the addition of cement to the tailings will bind some of the solutes to the cured tailings matrix. Cincilla et al (1997) suggest that the geochemistry of tailings paste can be readily modified to improve its environmental behavior. Further discussion of these aspects is given in the Jabiluka PER and in a report by Waite et al (1998). In addition, further investigations will be carried out as part of the ERA research program alluded to above. The values of tailings solute concentrations in table 6.3.1 have been used in examples given in section 6.3.4 because they are conservative.

Table 6.3.1 Model parameters for important solutes in the Jabiluka tailings

Solute	Concentration in Tailings*	Retardation Factor, R_f	Distribution Co-efficient, K_d
Uranium	15Bq/L	20	1
Radium	15Bq/L	100	5
Magnesium	5,000mg/L	1	0
Sulphate	20,000mg/L	1	0
Manganese	500mg/L	30	1.5

* Concentrations have been estimated using data for the geologically similar Ranger tailings

In table 6.3.1, K_d is the distribution co-efficient (see Eq (1) in Kalf & Dudgeon 1999) which describes the amount of the solute which will be retarded through absorption, precipitation/dissolution and complex ion-exchange reactions in the aquifer. The value of K_d is linearly related to the retardation factor, R_f, of the solute used in the model.

6.3.4 Predicted downstream concentrations of tailings derived solutes

The groundwater modelling indicated that the upward component of groundwater flow is weak in both the groundwater movement to the east towards Swift Creek and to the west towards the Magela floodplain. The flow was found to be predominantly horizontal, implying that only a small fraction of the groundwater in the deeper aquifer would be accessible to surface waters. All of the calculated groundwater concentrations discussed below refer to concentrations in the deep aquifer. Surface aquifer concentrations arising from the tailings repositories will be much lower. Regular annual flushing of the surface aquifer in the Wet season will ensure that there is a high degree of additional dilution and no build-up of contaminants in this zone.

Sources of the modelled solutes were the tailings silos for groundwater flows to the east, and the tailings deposited in the mined out stopes for flow to the west (see fig 6.3.3). As a test, Monte Carlo calculations were run initially by Kalf and Dudgeon (1999) for 255, 500 and 1000 random selections of the values of the variables. When little difference was found

between the runs, 255 random selections were used subsequently for simplicity. The parameters varied for the Monte Carlo calculations were the dispersivity, aquifer porosity, Darcy velocity and retardation. The range used for each parameter is listed in table 6.3.2.

Table 6.3.2 Parameter ranges used in the Monte Carlo analysis

Parameter	Range
Longitudinal Dispersivity α_L	1 m to 10 m
Transverse Dispersivity α_T	0.1 m to 1m
Vertical Dispersivity α_V	0.01 to 0.1 m
Darcy Velocity v_D	5×10^{-5} m/day to 5×10^{-6} m/day (East) 5×10^{-4} m/day to 5×10^{-5} m/day (West)
Effective Porosity P_a	0.005 to 0.10

In the lower permeability aquifer to the east of Jabiluka, the concentrations of non-reactive solutes reduce to negligible levels 200 m from the mine. For example, the median sulphate concentration profile relative to the 'source' concentration immediately downstream from the silos is given in figure 6.3.5. This solute profile was obtained for a 200 year run with a tailings permeability of 10^{-9} m/s and an aquifer conductivity of 0.01 m/d. If the tailings concentration of sulphate, which is the most mobile of the solutes considered, is 20,000 mg/L (table 6.3.1), the three-dimensional solute transport model shows that the concentration reduces to 2000 mg/L immediately downstream of the silo (Kalf & Dudgeon 1999). The data in figure 6.3.5 show that the median sulphate concentration reduces to 20 mg/L at a distance 100 m downstream. Given the large additional dilutions through the surficial aquifer before the contaminant can reach Swift Creek, then additional dilution in the creek itself, Kalf and Dudgeon (1999) conclude that there is negligible potential for contamination of surface streams to the east.
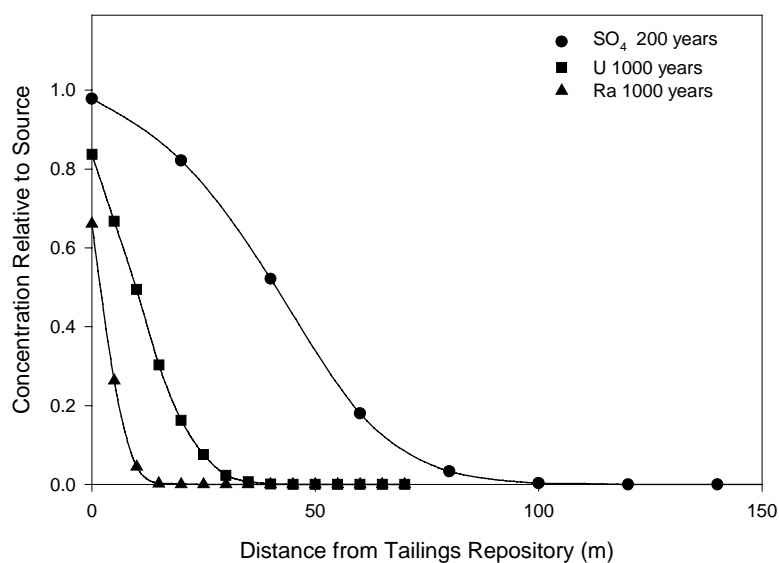

Figure 6.3.5 Variation of the median concentrations of SO_4, U and Ra with distance east of the tailings silos at Jabiluka. Concentrations are expressed as ratios to the 'source' concentration immediately downstream of the silos. The SO_4 concentrations were calculated 200 years after placement. The U and Ra concentrations were calculated 1000 years after placement.

The Monte Carlo simulations conducted for uranium using a paste permeability of 10^{-9} m/s indicated a contaminant front would move 50m downstream to the east after 1000 yrs. The maximum computed distance (which the Monte Carlo simulations indicated was of very low probability) was 300 m. For this paste permeability, which is at the upper end of range considered in the risk assessment process, the uranium concentration just outside the silos is predicted to be about 2.7 Bq/L and at 45 m from the silos it is predicted to fall to less than 1 mBq/L. The latter value is much less than naturally occurring concentrations in groundwater in the region which are about 30 mBq/L. For the median result, the distance for radium transport to the east was less than 15 m at which point the concentration would be less than 1 mBq/L, again much less than naturally occurring concentrations.

The transport of solutes to the west is calculated to be somewhat more rapid because of the greater permeability of the aquifer there. The velocities east of the divide in the sandstone are between $5x10^{-5}$ and $5x10^{-6}$ m/day, whilst in schists to the the west the range is $5x10^{-4}$ to $5x10^{-5}$ m/day. The results obtained for the migration of sulphate, uranium and radium to the west are shown in figure 6.3.6. These data indicate a probable migration distance of 500 m after 200 years for sulphate, although greater distances are possible (Kalf & Dudgeon 1999). Again, the three dimensional solute transport model shows that for a tailings permeability of 10^{-9} m/s, the sulphate 'source' concentration immediately downstream from the mine void tailings would be about 2000 mg/L. The data in figure 6.3.6 show that the median concentration of sulphate would drop to less than 20 mg/L about 500 m downstream. This water would be entering an area of already very poor quality water (see section 6.3.1) where natural sulphate concentrations are in the range 1500–7000 mg/L so that the impact of the migration of water from the tailings repository would be negligible. In addition, the floodplain is underlain by low permeability clays (East et al 1992) which act to limit any potential upflow of the groundwater into surface waters.
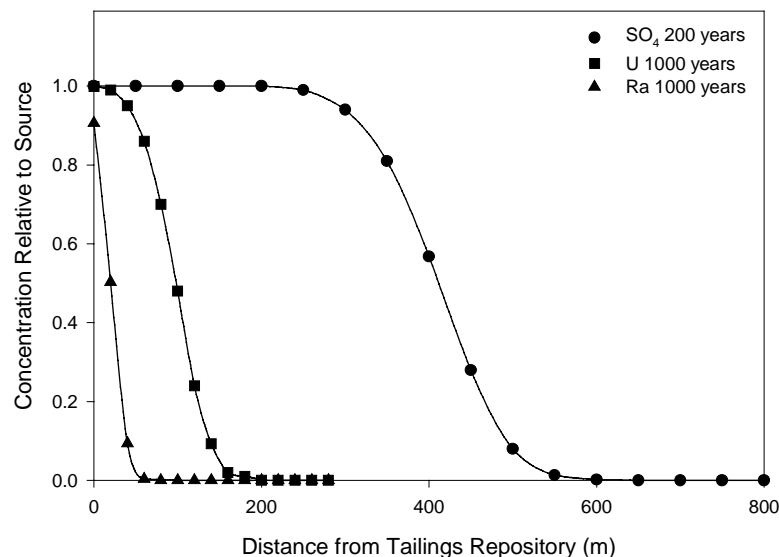
Figure 6.3.6 Variation of the median concentrations of SO_4, U and Ra with distance west of the tailings in the mine void at Jabiluka. Concentrations are expressed as ratios to the 'source' concentration immediately downstream of the void. The SO_4 concentrations were calculated 200 years after placement. The U and Ra concentrations were calculated 1000 years after placement.

The data in figure 6.3.6 indicate that uranium is likely to travel up to 200 m in a westerly direction at which point the concentration would be reduced to less than 1 mBq/L, a concentration that is significantly less than natural concentrations in the region. The Monte

Carlo calculations show that migration up to 1200 m is possible but with a very low probability. Kalf and Dudgeon (1999) conclude that radium and uranium will remain at background levels in the floodplain.

Kalf and Dudgeon (1999) also concluded that there is negligible likelihood of a major fracture system in the rock aquifer that could cause significant pollution in downstream waterways.

6.4 Risk assessment on the long-term storage of tailings

A risk assessment of the probable impact on people and the wetlands of Kakadu National Park arising from the long-term storage of tailings in the mine void and the silos has not been carried out to the extent that was developed in chapter 5 for storage of uranium on the surface.

To carry out such an assessment would require the extension of the analysis of groundwater dispersion to the quantitative prediction, using Monte Carlo analysis methods, of the concentrations of solutes in the waters of the Magela floodplain and the probability with which these concentrations will occur. The range and quality of existing hydrogeological data do not enable such a detailed analysis to be carried out. However, the Monte Carlo analyses of solute concentrations in the deep aquifer and the information on the vertical component of groundwater flow presented in section 6.3 demonstrate that the concentrations of the tailings derived solutes in surface waters of the Magela floodplain will remain at their natural values and will not be affected by dispersion of solutes from the tailings repositories.

6.5 Summary of findings on long-term storage of tailings

Erosion of tailings in the long-term
- Once the Jabiluka mine is backfilled and sealed following completion of mining, the only mechanism for physical dispersal of the tailings solids will be erosion of the overlying bedrock. Since the mine void and the tailings silos will be about 100 m below the surface and the upper surface of these is below sea level, the whole land mass would need to be eroded away and by that time the wetlands of Kakadu would no longer exist. Thus, physical dispersal of the tailings does not pose a threat to the wetlands of Kakadu.

- Using the mean measured denudation rate for the region of 0.04 mm per annum, the time required to erode the bedrock overlying the tailings in the mine void and the silos would be about 2 million years. Hence the excess concentrations all of the radioactive progeny will have decayed away by the time the tailings are exposed and they will be in approximate equilibrium with the residual uranium.

- Dispersal of tailings in the very long term will not constitute a hazard for future generations.

Hydrogeological features of the area
- The permeability of the Cahill Formation schists west of the orebody is significantly greater than that of the Kombolgie sandstone to the east. For this reason, it is recommended that the additional tailings silos should be excavated in the Kombolgie sandstone east of the orebody, as is currently planned by ERA. This choice of location will minimise potential environmental impacts.

- The excavation of the silos will result in additional material being placed on the surface. The location of the silos in the sandstone rather than in the schists to the west is also

preferable from the perspective of minimising environmental hazards on the surface because the sandstone is relatively low in the concentrations of hazardous chemicals. This material will require additional attention during the rehabilitation phase, but control of potential impacts on surface waters will be straightforward.

- The quality of groundwaters in the vicinity of the Jabiluka orebody, both to the west in Mine Valley and to the east towards Swift Creek, is high. Soluble salt concentrations are relatively low and radionuclide concentrations are very low. It is concluded that there is very little movement of radionuclides into the groundwater aquifer from the orebody. In contrast, the groundwater underlying the acid sulphate soils of the Magela floodplain is of high salinity, is acidic, and has high sulphate concentrations. The observed sulphate concentrations are up to one third of the concentration of sulphate expected in the Jabiluka tailings.

Modelling of the dispersion of solutes in groundwater
- A two dimensional section finite element model was used to determine flow directions, head distributions and the range of velocities.

- A three dimensional numerical solute transport model was applied to determine the concentrations of solutes leached from the tailings paste material for use as the source concentrations in the analytical model.

- An analytical contaminant transport model was used to determine concentrations due to advection, dispersion in three co-ordinate directions and retardation. This model used as input the range of velocities and source concentrations determined from the first two models. This model was combined with Monte Carlo calculations to determine concentration profiles for a large number of different parameter values within selected ranges.

Properties and constituents of tailings
- Although limited information is available on Jabiluka tailings because the mine is not operational, physical properties of tailings at Ranger have been studied extensively. Ore at Jabiluka and the Ranger Mine originate from the same geological formation and will be subject to the same milling process. Hence the tailings from the two mines are expected to have similar physical and chemical properties.

- Work undertaken as part of this review shows that achieving a tailings permeability of less than 10^{-9} m/sec is desirable. Based upon the research carried out on Ranger tailings, it is concluded that 99% of tailings in the silos at Jabiluka would have a permeability of less than 10^{-9} m/sec. Similar results are expected for tailings in the mine void but care will need to be exercised in placement of tailings in the mine void to avoid segregation and extensive residual voids.

- Research elsewhere on the effect of cementing the tailings paste indicates that the permeability of tailings will be reduced still further and may even reach a value which is lower than normal tailings by a factor of 1000.

- The addition of cement to the tailings will result in highly alkaline conditions which will reduce the availability of metals and radionuclides for dispersion from the tailings mass in groundwater.

- The conclusion of this review is that there is a very high probability of achieving a permeability in the cemented tailings that is less than 10^{-9} m/sec.

Predicted concentrations of solutes in the environment

- Modelling of the concentrations of solutes in the deep aquifer east of the tailings repositories in the direction of Swift Creek predicts that, after 200 years, sulphate concentrations should not exceed 20 mg/L even at distances as short as 100 m from the repositories. Uranium is not expected to move more than 50 m in 1000 years and for radium this distance is 15 m. The maximum distance moved by uranium under the most extreme (and very low probability) scenario considered in the Monte Carlo analysis is 300 m. Concentrations of uranium and radium at these distances will be negligible compared to naturally occurring concentrations.

- The transport of solutes to the west of the repositories is expected to be more rapid because of the higher permeability of the schists compared to that of the sandstone. Monte Carlo calculations indicate a probable migration distance of 500 m after 200 years for non-reactive solutes including sulphate, although greater distances are possible. The tailings derived solutes would be entering an area of already very poor quality water where natural sulphate concentrations are in the range 1500–7000 mg/L so that the impact of the migration of water from the tailings repository would be negligible. In addition, the floodplain is underlain by low permeability clays which act to limit any potential upflow of the groundwater into surface waters.

- The Monte Carlo calculations indicate that uranium is likely to travel up to 200 m in a westerly direction in about 1000 years at which point the concentration would be reduced to less than 1 mBq/L, a concentration that is significantly less than natural concentrations in the region. The calculations show that migration of uranium by up to 1200 m is possible but with a very low probability. It is concluded that radium and uranium will remain at background levels in the Magela floodplain.

- The groundwater modelling indicates that the upward component of groundwater flow is weak in both the groundwater movement to the east towards Swift Creek and to the west towards the Magela floodplain. The flow was found to be predominantly horizontal, implying that most of the solutes from the tailings repository will remain in the deep aquifer and move under the floodplain towards the sea. Only a small fraction of the groundwater in the deeper aquifer would be accessible to surface waters. All of the calculated groundwater concentrations discussed above refer to concentrations in the deep aquifer. Surface aquifer concentrations arising from the tailings repositories will be negligible. Any contaminants reaching the surface aquifer will be diluted and flushed away during the annual Wet seasons.

- The overall conclusion is that the wetlands of Kakadu will not be harmed as a result of the dispersal of tailings constituents in groundwater.

Risk assessment on the long-term storage of tailings

- A risk assessment of the probable impact on people and the wetlands of Kakadu National Park arising from the long-term storage of tailings in the mine void and the silos has not been carried out to the extent conducted for storage of uranium on the surface.

- To carry out such an assessment would require the extension of the analysis of groundwater dispersion to the quantitative prediction, using Monte Carlo analysis methods, of the concentrations of solutes in the waters of the Magela floodplain and the probability with which these concentrations will occur. The range and quality of existing hydrogeological data do not enable such a detailed analysis to be carried out.

- However, the Monte Carlo analyses of solute concentrations in the deep aquifer and the information on the vertical component of groundwater flow demonstrate that the concentrations of the tailings derived solutes in surface waters of the Magela floodplain will remain at their natural values and will not be affected by dispersion of solutes from the tailings repositories.

7 General environmental protection issues

7.1 Protection of the environment in the Alligator Rivers Region

Full details on the management arrangements for Kakadu National Park, the regulatory arrangements governing the mining of uranium in the Region, the supervisory responsibilities of the Commonwealth Government exercised through the Supervising Scientist, and the record of protection of Kakadu from environmental impact are presented in Johnston and Needham (1999) (Attachment A, 'Protection of the environment near the Ranger uranium mine').

The standard of environment protection that has been demanded by the Supervising Scientist has, from the commencement of mining in the Region, been among the highest in the world. Key in environmental protection are the Ramsar listed wetlands within the Kadadu National Park World Heritage Area. These seasonal wetlands present the greatest potential for damage from anthropic activity and have always received the highest attention from the Supervising Scientist. For the protection of these aquatic ecosystems, a control regime was implemented that was based on both chemical and biological assessment. In both cases, the approach adopted was consistent with the principles of Sustainable Development (Brundtland 1988) but was many years in advance of the international adoption of these principles.

Given the very high value attributed to Kakadu National Park by the Australian Government and the Australian community, the policy adopted in the development of chemical receiving water standards was that concentrations of chemical constituents should not be allowed to depart significantly from their 'natural' values unless there existed strong scientific evidence that any proposed change would not give rise to biological or chemical impact. Based on this policy, a strategy for development of appropriate standards was derived. In brief, a criterion that was considered conservative by biological scientists was adopted to determine what change from natural values could be assessed as not being biologically significant. A site specific assessment was then made to determine which chemicals would not meet this criterion, were waters to be discharged from the Ranger mine. These chemicals were considered 'critical constituents'. The available scientific data for this small number of critical constituents were examined to determine their adequacy for the setting of appropriate standards. For those for which the data were inadequate, toxicological tests were carried out on local native species to derive suitable standards.

This approach, developed by the Supervising Scientist, was accepted by the Australian and Northern Territory Governments. Water quality standards were then able to be deduced and applied more widely in the region. In retrospect, the policy can be seen as what would now be described as a precautionary aproach.

Similarly, the policy adopted in developing biological methods for the control and monitoring of water discharges from the Ranger mine was that the procedures used in the water management system at the mine should result in no detectable change in the species and community diversity of a set of aquatic animals in waterbodies downstream from the mine site. The strategy for achieving this objective was to implement a regime of stringent ecotoxicological tests prior to the discharge of any water from the mine site and to implement an extensive program of biological monitoring.

The ecotoxicological tests determine the lowest concentration of the effluent in creek water at which a change is detected for some sensitive measure of the animal's health (the LOEC) and the highest concentration at which no effect is observed (the NOEC). These values are

then used to specify the minimum dilution for effluent when discharged into surface waters. In specifying this minimum dilution, a factor of safety is applied to give protection against within-species variability, between-species variability and statistical uncertainties. The choice of species tested was made following an extensive period of research by the Supervising Scientist during which about 20 different species of local aquatic animals and plants were examined to determine the most sensitive species to waters at Ranger and species that could be successfully bred and maintained in the laboratory. The large number of species examined, the use of local native species and the use of a safety factor in specifying the dilution are factors that make the testing program for release of water to the Magela system the most rigorous anywhere in Australia and possibly the world.

The biological monitoring program includes: (a) tests that enable a short-term assessment of the impact of release, so that immediate management action can be implemented should effects be observed, and (b) tests that assess the long-term impact of the mining operation on aquatic ecosystems. The short-term tests are essentially toxicological tests on certain species carried out in the field downstream from the mine and use sensitive endpoints (for example, survival of larval fish and the egg production rate of freshwater snails) in local native species. The long-term tests search for changes in species and community diversity by examining the community structure of fish and macroinvertebrates identified to the species level.

A full analysis of the results of these monitoring programs, as well as radiological monitoring programs, is presented in Johnston and Needham (1999). This report shows that the concentrations of all chemical constituents have, throughout the entire period of mining, remained below the standards recommended by the Supervising Scientist, that operation of the mine has had no detectable impact on a range of sensitive indicators of ecological health including the survival of larval fish, the reproduction of freshwater snails, the migration patterns of fish, and the community structure of fish and macroinvertebrates, and that the radiation exposure of people living in the vicinity of the mine, either through consumption of foods collected from downstream waters or through radon dispersed from the mine site, has always been significantly lower than the internationally recommended limit on radiation exposure of members of the public.

In summary, the environmental protection regime that the Australian Government implemented for the mining of uranium at Ranger has been completely consistent with the principles of Sustainable Development and it has been demonstrated, through an extensive chemical, biological and radiological monitoring program, that no impact of significance under those principles has occurred, on either people or ecosystems of Kakadu National Park, throughout the operation of the Ranger mine.

The same regulatory regime, but strengthened in some particular cases, would apply to the mining of uranium at Jabiluka.

7.2 The Ranger and the Jabiluka milling alternatives

The report of the Mission of the World Heritage Committee to Kakadu noted (section 7.3) that two options for the milling of ore from the Jabiluka mine have been proposed by ERA and assessed by the Government. These options are known as the Ranger Mill Alternative (RMA) and the Jabiluka Mill Alternative (JMA).

Under the RMA option, ore would be transported from Jabiluka to the Ranger mine site where it would be processed in the existing mill. Transportation would be along a specially constructed road 22.5 km in length. No part of this road would be in Kakadu National Park. All tailings produced from the milling of the Jabiluka ore would be deposited in the mined-

out pits at Ranger along with the tailings produced from the milling of Ranger ore. Following completion of mining, the pits would be covered with inert waste rock and revegetated. All waste rock produced at Jabiluka would be used as cemented backfill in the mine void. In addition, some of the waste rock and low grade ore at Ranger would be transported to the Jabiluka site and used as cemented backfill in the mine void. The only surface facilities at Jabiluka would be an ore stockpile, a waste rock stockpile and a water retention pond to collect and store all rainfall runoff from the stockpiles and water pumped from the mine. No water would be discharged from the mine. Following completion of mining, the pond would evaporate to dryness over several years and the site would be rehabilitated.

Under the JMA option, which is the subject of this review, a mill would be constructed at Jabiluka to process the ore. All tailings would be dewatered to form a paste to which would be added concrete and the concrete paste would be returned underground to the mine void and to silos excavated underground, probably in the sandstone to the east of the orebody. The excavated sandstone would be placed in stockpiles on the surface at Jabiluka. All water pumped from the mine and rainfall runoff from the mill and ore stockpile would be collected and stored in a water retention pond. Rainfall runoff from the sandstone stockpiles would freely discharge to Swift Creek but ERA would, as specified by the Minister for the Environment, be required to take whatever steps are necessary to ensure that suspended solids concentrations in Swift Creek do not rise significantly above natural values.

Because the JMA option requires the construction of a mill at Jabiluka and requires additional waste rock stockpiles, the RMA option is preferred both by ERA and the Government. However, the RMA option requires the specific approval of the traditional owners and this approval has not been given. It is for this reason that ERA proposed the JMA option. The Mission report was critical of ERA for proposing to proceed with the JMA option 'despite not being the preferred environmental option'. This review, however, and the original assessment of the JMA proposal by Environment Australia have shown that, while the RMA option is preferred, the risk to the environment arising from the JMA option is minimal and, in particular, that the wetlands of Kakadu National Park will not be threatened if the project proceeds.

7.3 Location and extent of the Jabiluka ore body

The extent of the No 2 orebody at Jabiluka has not been fully delineated at depth in that section of the orebody to the east of the Hegge fault (see for example fig 6.4 of the EIS). It is the intention of ERA to carry out further drilling once the decline reaches the orebody in an attempt to establish whether or not further reserves of uranium exist.

The possibility of finding further uranium ore at depth was assessed in the Environment Assessment report on ERA's proposal at the EIS stage. The primary issue considered was the capacity of the two pits at Ranger for the disposal of tailings from both the Ranger deposits and tailings from Jabiluka. The Government decided that, when placed in the pits at Ranger, tailings from the combined operations at Ranger and Jabiluka should not exceed specified depths below the ground surface. The effect of this decision is to restrict mining at Jabiluka to the currently delineated orebody. Any proposal to mine more uranium than would satisfy this requirement will require further assessment under the *Environment Protection (Impact of Proposals) Act 1974*. Hence, if the Ranger Mill Alternative were to proceed, the mining at Jabiluka would be restricted to the currently delineated orebody and the period of mining would be about 30 years.

If the Jabiluka Mill Alternative proceeds, however, the issue of adequate capacity for disposal of the tailings from Jabiluka does not arise because all tailings will be returned underground. The mining and milling of any additional reserves of uranium would result in return of the additional tailings produced to the additional mine void and to additional silos excavated for the purpose. There would be no need for further assessment under the *Environment Protection (Impact of Proposals) Act 1974.*

7.4 Landscape-wide analyses

Wasson et al (1998) suggest that the landscape context of the mine proposal has been inadequately addressed. The EIS did contain some detail on the vegetation associations using the work of Wilson et al (1990a and b), the authoritative work on vegetation in the Northern Territory. The Jabiluka mine will be a point impact, with some specific potential effects, which are addressed in the main body of this report. It is simply not true to suggest that the EIS and PER are inadequate because they have not considered a 'Kakadu National Heritage Park' (*sic*) scale.

The potential impact on wetlands is, however, considered to be a key element of the environmental protection associated with Jabiluka, as it is with Ranger. The potential effects of any environmental impacts will arise from groundwater intrusion, and from accidental impacts on surface features. Such impacts have been included in the work contained in the EIS/PER, and have been subjected to further critical review in this report.

While it is true the sort of digital terrain modelling contained in Wasson et al (1998) is not included in the EIS/PER, it is not considered necessary or appropriate to determine the safety of the mine proposal. Further, the suggestion that Jabiluka is 'the only escarpment unit adjacent to the swamp ecosytem' is untrue. The term swamp ecosystem suggests a uniformity that a casual examination shows to be false — the floodplains are a very complex spatial and temporal mix of vegetation and faunal communities. Jabiluka, as an outlier of the escarpment, is similar to Mt Brockman, Nourlangie Rock, Mt Basedow and others. The Jabiluka site does have a very rich landscape texture, derived from a complex mix of topography and surface geology. The Jabiluka project, however, will not have any long-term effects on this landscape texture.

The assertion that the context modelling for the minesite need be broader than is currently the case is therefore rejected.

7.5 Acid sulphate soils

The submission of Wasson et al (1998) notes the existence of acid sulphate soils on the Magela floodplain downstream from the Jabiluka mine site and proposes that these soils could give rise to the following concerns:

(i)   Heavy metals accidentally released from the mine site could be mobilised into downstream ecosystems by acid from the soils, and

(ii)   Developments associated with the mine, such as the pumping of water from a billabong to service the Ja-Ja camp, could lead to increased acidity in surface waters.

With respect to the second of these concerns, the proposal to re-establish the old Ja-Ja camp, which was outlined in the Supplement to the EIS (section 5.4.2), was withdrawn in the PER on the Jabiluka Mill Alternative (section 4.3.7). As a result, there is now no intention to pump 10,000 L of water per day from the billabong. Water requirements will be limited to

the daily supply for one security officer. This requirement will, therefore, not cause any increase in acidity in surface waters.

The first concern recognises that, even in a well designed system with inbuilt first and second order levels of protection, occasional accidents can occur resulting in the unplanned release of contaminants. However, experience at the Ranger mine has shown that in every case where incidents have occurred, the total load of any metals released is extremely small compared to the natural load of metals in the soils of the floodplain. Hence, the impact of these accidental releases has been, and can with confidence be expected to be, insignificant compared to that arising from the naturally occurring metals in the soils of the floodplain.

7.6 Rehabilitation of the Jabiluka lease area

The Commonwealth Government, in its environmental requirements for the Jabiluka mine, requires ERA to rehabilitate the mine site in a manner which will establish an environment in the lease area that reflects to the maximum extent that can reasonably be achieved, the environment existing in the adjacent areas of Kakadu National Park. The intention of the rehabilitation is that the rehabilitated area could be incorporated into the Kakadu National Park without detracting from park values. These requirements are the same as apply to the Ranger Project Area.

The major objectives of rehabilitation are:

(a)   to revegetate the disturbed sites of the lease area with local native plant species similar in density and abundance to that existing in adjacent areas of Kakadu National Park, in order to form an ecosystem the long term viability of which would not require a maintenance regime significantly different from that appropriate to adjacent areas of the park;

(b)   to establish stable radiological conditions on disturbed sites of the lease area so that, with a minimum of restrictions on use of the area, the public dose limit will not be exceeded and the health risk to members of the public, including traditional owners, will be as low as reasonably achievable;

(c)   to limit erosion in rehabilitated areas, as far as can reasonably be achieved, to that characteristic of similar landforms in surrounding undisturbed areas.

The Government has established secure mechanisms to ensure that these rehabilitation objectives will be achieved even if the company becomes insolvent and ceases operations prior to the completion of adequate rehabilitation of the sites.

In accordance with the Ranger Uranium Project Government Agreement between the Commonwealth and ERA, a rehabilitation plan is submitted each year by ERA to the Department of Industry, Science and Resources (DISR). Its purpose is to provide the basis for estimating the appropriate size of the Ranger Rehabilitation Trust Fund, an ongoing contingency for the cost of rehabilitation of the Ranger Project Area if mining operations were to cease at the date of the preparation of the plan. The Supervising Scientist provides comment to the DISR on each rehabilitation plan.

The Jabiluka Rehabilitation fund comprises a Bank Guarantee deposited with the NT Department of Mines and Energy to provide a basis for rehabilitating the site if operations were to cease. The amount of this Bank Guarantee is the estimated cost of rehabilitation plus a contingency factor. As with the Ranger Rehabilitation Plan, the Jabiluka Rehabilitation Plan was submitted to the Supervising Scientist for comment before acceptance.

7.7 Transport of uranium from the Jabiluka mine

The transport of uranium product is subject to the requirements of the Northern Territory *Radioactive Ores and Concentrates (Packaging and Transport) Act*. Under this act, any transport of uranium product outside the boundaries of the Jabiluka mine lease or the Ranger Project Area is forbidden except in accordance with a current Licence to Transport Radioactive Material issued under that Act. Further, the storage of uranium product outside the boundaries of the Jabiluka mine lease or the Ranger Project Area is also forbidden except in accordance with a current Licence to Store Radioactive Material.

Together, these two legal instruments specify the route that must be followed, the places where the uranium product may be stored *en route* to the Port of Darwin, the security measures which must be in place, the communication and emergency equipment which must be available, and the training requirements for the person in charge of the vehicles conveying the uranium product. They also require that the uranium product be packaged and transported in accordance with the *Code of Practice for the Safe Transport of Radioactive Substances 1990*, which includes the total text of the International Atomic Energy (IAEA) Regulations for the Safe Transport of Radioactive Material.

Uranium product is insoluble powder with a low specific activity (radiation concentration). It is predominantly an alpha and beta particle emitter, however, it also emits low levels of gamma radiation. The hazard associated with uranium product is the inhalation of particles in the respirable size range.

The requirements for the packaging and transport of uranium product are designed to minimise the risk from that hazard. Uranium product is contained within sealed and lined 205 litre drums. The drums are arranged within purpose built racks to prevent movement and are secured within standard freight containers that are locked using tamper evident devices. The transport containers are then conveyed on trucks to the Port of Darwin, from which they are loaded on to a cargo vessel for export.

Each 205 litre drum is individually labelled in accordance with the IAEA Transport Regulations, as is each freight container. Each truck carrying uranium product carries emergency equipment including a first aid kit, dust masks, and other items which would enable the driver to safely establish a cordon around any spilled material.

In addition, two emergency trailers and trained emergency response crews are on call for each consignment of uranium product. The trailers contain equipment that would allow the crew to safely collect any spilt uranium product.

If a transport accident occurred resulting in a spillage of uranium product, the dominating hazard would be due to the inhalation of the product. The emergency procedures and equipment are designed to minimise the inhalation of product to trivial levels, however, it is possible that non-trivial exposure could occur to a person who was incapacitated in the transport accident. Assuming that a person without respiratory protection was exposed to air with a moderately high dust loading of one milligram per cubic metre of uranium product, it would take several hours for that person to inhale enough product to result in a committed effective dose equal to the annual dose limit for members of the public. This is a very unlikely scenario considering the response time of the emergency response crews. It should also be noted that there has never been a transport accident involving the release of uranium product during the life of the Ranger mine.

The hazard to the environment posed by uranium product is very low as it is an insoluble powder of low specific activity. Decontamination of an area that has been contaminated with

uranium product is a simple task. Depending on the volume of product spilt and the area over which the spill is spread, industrial vacuum cleaners, or standard earthmoving equipment could be used. Any remaining product could be readily identified using standard radiation detection equipment allowing an effectively complete decontamination of the area which would preclude any possibility of environmental impact.

7.8 Summary of findings on general environmental protection issues

The conclusions of the Supervising Scientist on the above general environmental protection issues are:

Protection of the environment in the Alligator Rivers Region

- The environmental protection regime that the Australian Government implemented for the mining of uranium at Ranger has been completely consistent with the principles of Sustainable Development and it has been demonstrated, through an extensive chemical, biological and radiological monitoring program, that no impact of significance under those principles has occurred, on either people or ecosystems of Kakadu National Park, throughout the operation of the Ranger mine.

- The same regulatory regime, but strengthened in some particular cases, would apply to the mining of uranium at Jabiluka.

The Ranger and the Jabiluka milling alternatives

- The Mission report was critical of ERA for proposing to proceed with the Jabiluka Mill Alternative (JMA) option 'despite not being the preferred environmental option'. This review, however, and the original assessment of the JMA proposal by Environment Australia have shown that, while the RMA option is preferred, the risk to the environment arising from the JMA option is minimal and, in particular, that the wetlands of Kakadu National Park will not be threatened if the project proceeds.

Location and extent of the Jabiluka ore body

- The extent of the No 2 orebody at Jabiluka has not been fully delineated at depth in that section of the orebody to the east of the Hegge fault. If the Ranger Mill Alternative were to proceed, the mining at Jabiluka would be restricted to the currently delineated orebody and the period of mining would be about 30 years unless approval is given by the Commonwealth to mine any additional reserves following assessment under the *Environment Protection (Impact of Proposals) Act 1974*.

- If the Jabiluka Mill Alternative proceeds, there would be no need for further assessment of a proposal to mine additional reserves under the *Environment Protection (Impact of Proposals) Act 1974*.

Landscape-wide analyses

- Wasson et al (1998) suggest that the landscape context of the mine proposal has been inadequately addressed. The Jabiluka mine will be a point impact, with some specific potential effects, which are addressed in the main body of this report and shown to be negligible. It is simply not true to suggest that the EIS and PER are inadequate because they have not considered potential impacts across the whole of Kakadu National Park. The assertion that the context modelling for the minesite need be broader than is currently the case is therefore rejected.

Acid sulphate soils

- The concerns of Wasson et al (1998) that heavy metals accidentally released from the mine site could be mobilised into downstream ecosystems by the acid sulphate soils and that the pumping of water from a billabong could lead to increased acidity in surface waters are not justified. Experience at the Ranger mine has shown that in every case where accidental releases have occurred, the total load of any metals released is extremely small compared to the natural load of metals in the soils of the floodplain. The previous proposal to re-establish the old Ja-Ja camp has been withdrawn and there are no plans to pump large quantities of water from the billabong.

Rehabilitation of the Jabiluka lease area

- ERA is required to rehabilitate the Jabiluka mine site in a manner which will establish an environment in the lease area that reflects, to the maximum extent that can reasonably be achieved, the environment existing in the adjacent areas of Kakadu National Park. The intention is that the rehabilitated area could be incorporated into the Kakadu National Park without detracting from park values.

- The Government has established secure mechanisms to ensure that these rehabilitation objectives will be achieved even if the company becomes insolvent and ceases operations prior to the completion of adequate rehabilitation of the sites.

Transport of uranium from the Jabiluka mine

- The transport of uranium product from Jabiluka to the Port of Darwin through Kakadu National Park is governed by laws of the Northern Territory which include the total text of the International Atomic Energy Agency Regulations for the Safe Transport of Radioactive Material.

- Two emergency trailers and trained emergency response crews are on call for each consignment of uranium product. The trailers contain equipment that would allow the crew to safely collect any spilled uranium product. The hazards associated with spillage of uranium product have been carefully assessed and emergency procedures have been developed to ensure that both people and ecosystems will be protected in the event of an accident.

- There has never been a transport accident involving the release of uranium product during the life of the Ranger mine.

8 Conclusions

This report has been prepared in response to the request of the World Heritage Committee that the Supervising Scientist conduct a full review of scientific issues raised by the Committee's Mission to Kakadu National Park in October–November 1998. Perceived scientific uncertainty with respect to these issues had led to the Mission's conclusion that the natural values of Kakadu are threatened by the Jabiluka project.

It must be emphasised that this report does not purport to be a complete environmental impact assessment of the Jabiluka project. There are many environmental protection issues related to the development of Jabiluka that were not raised in the Mission's report or in the decision of the World Heritage Committee. These broader issues have already been addressed in the environmental impact assessment process to which the Jabiluka project was subjected and are covered by the requirements that the Commonwealth Government imposed in granting its approval for the project to proceed.

This report includes a thorough review of all of the issues raised by the World Heritage Committee and provides a detailed assessment of the risks to the wetlands of Kakadu arising from the storage of uranium ore at the surface at Jabiluka, the management of water and the storage of tailings.

Before summarising the reports conclusions, it is pertinent to a provide brief comment on the environmental impact assessment process in Australia. For a project of environmental significance, any Commonwealth approvals may only be given following environmental assessment under the Commonwealth's *Environment Protection (Impact of Proposals) Act 1974*, the EPIP Act. A similar process is also required under State or Territory legislation and, where both are required, these processes may be carried out jointly under Commonwealth and State or Territory law.

The intent of the EPIP Act, and its State/Territory counterparts, is to ensure that matters affecting the environment to a significant extent are fully examined and taken into account in decisions taken by the Commonwealth and State/Territory governments. The proponent must describe the design of the project in sufficient detail that the likely environmental impact arising from the project can be adequately assessed. However, the detailed design of the project may not have been completed prior to submission of the EIS. The detailed design of the project would normally be completed after approval has been given for the project to proceed under the EPIP Act process so that any environmental conditions can be included within final design parameters. Recognition is given to the fact that each State and Territory has in place a regulatory regime under which detailed aspects of a project are assessed and specific authorisations and approvals are granted.

In the case of uranium mining in the Alligator Rivers Region of the Northern Territory, specific authorisations and approvals are granted by the responsible Northern Territory Minister under the *Uranium Mining (Environmental Control) Act 1979*. Under the Working Arrangements agreed between the Commonwealth and Northern Territory Governments, the Supervising Scientist reviews the environmental aspects of all detailed proposals that might be the subject of such authorisations and approvals and provides advice to the Northern Territory on the environmental consequences. It is through this process that the detailed design of the Jabiluka project would be assessed and approved.

Many of the issues that were raised by the report of the Mission of the World Heritage Committee come into the category of detailed design. That is, many of the issues had been identified by the Supervising Scientist and others as being issues that would need to be

resolved by the proponent in consultation with officials of the Northern Territory and the Supervising Scientist at the detailed design stage but the conclusion had been reached that there were no insurmountable obstacles that would prevent a design being achieved that would ensure the highest level of environmental protection in Kakadu National Park.

This detailed review has demonstrated that there were a number of weaknesses in the hydrological modelling presented by ERA in the EIS and the PER. Accordingly, a number of recommendations have been made which should be implemented by ERA in completing the detailed design of the Jabiluka project. On the other hand, the review has demonstrated quite clearly that, if the design of the water management system proposed by ERA in the PER *had* been implemented, the risk to the wetlands of Kakadu National Park, and the risk of radiation exposure to people of the region would have been extremely low. This conclusion is valid even in extreme circumstances leading to the complete failure of the structure of the water retention pond at Jabiluka.

The lay reader will, no doubt, find this conclusion surprising. Its origin, however, lies in the fact that uranium is not a particularly toxic substance for aquatic animals. It has been well established that the toxicity of uranium is much lower than that of many many more common substances such as copper, cadmium and lead. It is the perception of the public that uranium is a very dangerous substance, and the failure of the scientific community to persuade the public otherwise, that has led to adoption of extreme measures to ensure that no amount of uranium should leave the site of a uranium mine.

Similarly, uranium in its natural state does not pose a particularly severe radiation threat. Exposure to uranium and its radioactive progeny needs to be controlled but the inherent radioactivity of uranium and its progeny is sufficiently low that ensuring that people do not receive exposures that would be harmful is relatively straightforward. It is only when uranium is used as fuel in a reactor that fission reactions result in a large number of radioactive products which produce high levels of ionising radiation.

Thus, on scientific grounds, there is no reason why water collected at Jabiluka could not be discharged into the surface waters of the Magela floodplain under a suitably designed control regime that would protect both people and ecosystems. The proposal by ERA that these waters should be totally contained at the mine site was made in response to social concerns and perceptions, not scientific evidence.

The long-term threats to the wetlands of Kakadu arising from the storage of uranium mill tailings at Jabiluka have also been assessed. Because the tailings will be stored at a significant depth below the surface of the land, physical dispersion of the tailings will not be possible for millions of years. The whole land mass would need to be eroded away and by that time the wetlands of Kakadu would no longer exist. Even then, the threat to future generations is insignificant because the residual uranium and its radioactive progeny would be present at low concentrations and would be mixed, when dispersed, with the inert material surrounding the current orebody. Dispersion of radionuclides and other constituents of the tailings in groundwater has been shown to present no threat to the wetlands of Kakadu or the people who live there in either the short-term or the long-term.

The conclusion of this review, therefore, is that, contrary to the views expressed by the Mission, the natural values of Kakadu National Park are not threatened by the development of the Jabiluka uranium mine and the degree of scientific certainty that applies to this assessment is very high. There would appear, therefore, to be no justification for a decision by the World Heritage Committee that the natural World Heritage values of Kakadu National Park are in danger as a result of the proposal to mine uranium at Jabiluka.

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Attachments to this report

Attachment A

Johnston A & Needham S 1999. *Protection of the environment near the Ranger uranium mine,* Supervising Scientist Report 139, Supervising Scientist for the Alligator Rivers Region, AGPS Canberra, (in press).

Attachment B

Bureau of Meteorology 1999. *Hydrometeorological analysis relevant to Jabiluka.* Supervising Scientist Report 140, Supervising Scientist for the Alligator Rivers Region, AGPS Canberra, (in press).

Attachment C

Jones RN, Hennessy KJ & Abbs DJ 1999. *Climate change analysis relevant to Jabiluka.* Supervising Scientist Report 141, Supervising Scientist for the Alligator Rivers Region, AGPS Canberra, (in press).

Attachment D

Chiew F & Wang QJ 1999. *Hydrological analysis relevant to surface water storage at Jabiluka*, Supervising Scientist Report 142, Supervising Scientist for the Alligator Rivers Region, AGPS Canberra, (in press).

Attachment E

Kalf F & Dudgeon C 1999. *Analysis of long term groundwater dispersal of contaminants from proposed Jabiluka mine tailings repositories.* Supervising Scientist Report 143, Supervising Scientist for the Alligator Rivers Region, AGPS Canberra, (in press).

Appendix 1

**World Heritage Committee
Twenty-second session
Kyoto, Japan
30 November – 5 December 1998**

Decision on Kakadu National Park

The Committee recognised the report of the mission to Kakadu National Park as being both thorough and credible. The Committee:

(i)   Expressed grave concern at the ascertained and potential dangers to the World Heritage cultural and natural values of Kakadu National Park which, as noted in the Mission report, are posed primarily by the proposal for uranium mining and milling at Jabiluka;

(ii)   Noted with concern that in spite of the dangers to the World Heritage values, construction of the mine at Jabiluka began in June 1998 and is currently progressing;

(iii)   Has been informed by the Australian authorities that construction of the mine decline and site will proceed; however, in the next six months no mining of uranium will take place, the construction of the mill will not commence and an export permit for the Jabiluka uranium will not be issued. The Committee has also been informed that the Australian authorities will act to complete the cultural heritage management plan with independent public review and they will accelerate the implementation of the Kakadu Region Social Impact Study;

(iv)   Noted that there is significant difference of opinion concerning the degree of certainty of the science used to assess the impact of the mine of the World Heritage values of Kakadu (notably hydrological modelling, prediction and impact of severe weather events, storage of uranium ore on the surface and the long-term storage of the mine tailings);

(v)   Noted that the associative cultural values, and the archaeological and rock art sites, on the basis of which Kakadu National Park was inscribed on the World Heritage List, and the ability of affected Aboriginal communities to continue their traditional relationships to the land, are threatened by the Jabiluka mine proposal; and

(vi)   Emphasized the fundamental importance of ensuring thorough and continuing participation, negotiation and communication with Aboriginal traditional owners, custodians and managers in the conservation of the outstanding heritage values of Kakadu for future generations.

In view of the ascertained and potential dangers posed by the Jabiluka uranium mine that are noted in the report of the World Heritage mission to Kakadu, and have again been noted with concern by the Committee, IUCN, ICCROM and ICOMOS, the Committee decided the following:

1   In light of the concerns expressed by the Delegate of Australia, the Australian authorities be requested to provide, by **15 April 1999**, a detailed report on their efforts to prevent further damage and to mitigate all the threats identified in the

World Heritage mission, report to the World Heritage cultural and natural values of Kakadu National Park, Australia. The report should address these threats posed by the construction of the Jabiluka mine, by the mining of uranium ore at Jabiluka, and the alternatives for milling the ore at Jabiluka and Ranger. The report should be prepared in accordance with the intent of (v) above. The report submitted by the Australian authorities should include a detailed update on the implementation of the cultural heritage management plan referred to in (iii) above and in the mission report.

2 Immediately up its receipt by the Secretariat, the report referred to in paragraph 1 above, be provided to ICOMOS, ICCROM and IUCN, who will ensure that the twenty-third session of the Bureau of the World Heritage Committee, be provided with written independent expert review concerning the mitigation of threats posing ascertained and potential dangers to Kakadu National Park by the Jabiluka mine. The expert opinion of ICOMOS, ICCROM and IUCN will be provided to the Secretariat by **15 May 1999** for immediate distribution to members of the Bureau and the Australian authorities.

3 The Australian authorities be requested to direct the Australian Supervising Scientist Group to conduct a full review of the scientific issues referred to in Paragraph (iv) above, to be provided to the Secretariat by **15 April 1999**. The review will be submitted to peer review by an independent scientific panel composed of scientists selected by UNESCO in consultation with the International Council of Scientific Unions and the Chairperson of the World Heritage Committee. The report of the peer review will be provided to the Secretariat by **15 May 1999** for immediate distribution to the members of the Bureau, IUCN and the Australian authorities.

4 The reports referred to in Recommendations 1, 2 and 3 will be examined by the twenty-third session of the Bureau.

5 The twenty-second session of the Committee has decided that an extraordinary session of the Committee, to immediately follow the twenty-third session of the Bureau in July 1999, will be convened at UNESCO Headquarters to decide whether to immediately inscribe Kakadu National Park on the List of World Heritage in Danger.