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Review of mine-related research in the Alligator Rivers Region 1978–2002:

Prepared for ARRTC9 meeting, 25–27 February 2002

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Australian Government
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Supervising Scientist

It is SSD policy for reports in the SSR series to be reviewed as part of the publications process.

This SSR is a review of mine-related research in the Alligator Rivers Region 1978-2002 and has been reviewed internally by senior SSD and EWLS staff.

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Preface

Staff of the Supervising Scientist Division (SSD) and Earth Water Life Sciences (EWLS) have worked hard at providing this summary of research requested by the members of the Alligator Rivers Region Technical Committee at the ARRTC8 meeting on 8–9 December 2001. However, in its current form, the report needs to be considered a draft document. The task proved greater than most of us anticipated and the Christmas/New Year break certainly made it difficult to complete the task in the short time since the previous meeting.

As stated in the Introduction, what we have attempted to do is:

- Identify the major fields in which research has been necessary in the region to ensure that the environment of the region is protected from the effects of uranium mining,
- Summarise the major issues or problem areas in these fields and the scope of studies carried out,
- Summarise the principal outcomes for operation of mining in the region and for subsequent rehabilitation of mine sites
- Identify issues that still require scientific research to either ensure ongoing environmental protection to a very high standard during mining operations or to ensure rehabilitation of mine sites to the standard demanded by governments and the community.

To a large extent the first three of these tasks have been achieved but the current text is clearly a multi-authored document. Because there has been insufficient time for us to edit and restructure individual contributions, the review at the moment lacks the type of consistency of approach that we would prefer to achieve.

The fourth task listed above was the identification of issues requiring future research. While most contributors have tackled this task, there has been insufficient time to allow us to bring these proposals together in a final chapter in which we assess the various proposals, identify possible omissions, and present to ARRTC a consolidated ERA/SSD view that could form the basis of discussion at ARRTC on the future development of our respective research programs.

In addition, the reference list is extensive and includes many cases where multiple papers by the same authors have been published. Careful checking of these is still required.

For these reasons, we suggest that discussions at the ARRTC9 meeting on 25–27 February 2002 should concentrate on those aspects of the current report that describe past progarms of research rather than focussing too much at this stage on the issue of prioritising future research. We intend continuing work on the report over the next month or so and then publishing the report in the Supervising Scientist's report series. The question of prioritising future research could then be addressed at the next ARRTC meeting. We will welcome discussion of this proposed approach at the ARRTC9 meeting on 25–27 February 2002.

Arthur Johnston
Supervising Scientist
19 February 2002

Tony Milnes
General Manager, EWLS
19 February 2002

1 Introduction

This report has been prepared in reponse to a request from the members of the Alligator Rivers Region Technical Committee (ARRTC) at the ARRTC8 meeting of 8–9 December 2001. The objective is to summarise information on the mining-related research undertaken in the Alligator Rivers Region (ARR) since 1978 that will enable members to place current and proposed future research programs in context.

Several formal reviews of research in the region have been undertaken in the past. These include the Taylor review of Alligator Rivers Region Research Institute (renamed as the Environmental Research Institute of the Supervising Scientist, ***eriss,*** in 1994) in 1989/90 and the Barrow review in 1993/94. These reviews, because of their specific terms of reference, concentrated on the program of ***eriss***. In this report we attempt to integrate the research undertaken by ***eriss*** and its collaborators and consultants with that undertaken by Energy Resources of Australia (ERA), Earth Water Life Sciences (EWLS) and their consultants.

A comprehensive review of the mining related research in the ARR over the past 24 years is beyond the scope achievable in the short time available for the production of this report. What we have attempted to do is:

- Identify the major fields in which research has been necessary in the region to ensure that the environment of the region is protected from the effects of uranium mining,
- Summarise the major issues or problem areas in these fields and the scope of studies carried out,
- Summarise the principal outcomes for operation of mining in the region and for subsequent rehabilitation of mine sites
- Identify issues that still require scientific research to either ensure ongoing environmental protection to a very high standard during mining operations or to ensure rehabilitation of mine sites to the standard demanded by governments and the community.

Addendum to the introduction

The preface to this report identifies that it was produced in February 2002 in response to a request from the ARRTC8 meeting in December 2001.

It comprises a major body of work that was undertaken in a short time and, as such, the preface includes caveats essentially stating that the report requires more work before it could be considered to be complete.

It is not considered to be practicable to attempt to update it in its entirety prior to publication or to periodically rewrite the document to maintain its currency, but it was considered appropriate to add a later chapter, Chapter 6, that covers the Key Knowledge Needs (KKNs) that were developed by ARRTC, largely in response to the first release of this report as a work in progress.

Since 2002, and also subsequent to the development of the first iteration of the KKNs, there have been a number of new developments in the region that date the content of this report. With the exception of the KKNs, which were current from 2004 to 2006, the remainder of the report should be considered to be a snapshot of the status quo as at February 2002.

Since the release of the first KKNs in 2004, ***eriss*** has produced annual research summaries that are compatible with the KKN format. Some additional compilation will be required to catalogue research undertaken between February 2002 and commencement of the current annual research summary series.

Revision of the KKNs commenced in January 2007.

Alan Hughes, Supervising Scientist

February 2007

2 The Alligator Rivers Region

2.1 Description of the Region

The Alligator Rivers Region is of outstanding heritage value for its unusual combination of largely uninhabited areas with attractive wild scenery. It is highly biodiverse and has a very large concentration of Aboriginal rock art of world significance. Its national and international importance is recognised by the inclusion of Kakadu National Park (totally enclosed within the region) on the Register of the National Estate and its inscription on the World Heritage List. The floodplain areas within Kakadu are recognised as one of Australia's Wetlands of International Importance listed under the Convention on Wetlands of International Importance (the 'Ramsar' Convention).

The ARR is defined in Section 3(1) of the *Environment Protection (Alligator Rivers Region) Act* 1978. This current definition is based on the definition in the Ranger Uranium Environmental Inquiry Second Report but also includes the former Gimbat and Goodparla pastoral leases in the south following the declaration of Stage 3 of Kakadu National Park and the inclusion of the above leases within the boundary of the Park. The region (Figure 1) is about 220 km east of Darwin and comprises an area of about 28 000km^2. It includes the catchments of the West Alligator, South Alligator and East Alligator Rivers, extending east into Arnhem Land. The region also contains sections of the Katherine River catchment to the south and the Mary River and Wildman River catchments to the west.

The Region is rich in natural resources, having a variety of terrestrial and aquatic ecosystems including sandstone heathlands, open woodland, monsoon rainforest, flood plains, large rivers, seasonal water courses and permanent billabongs, as well as large mineral reserves including uranium, gold and platinum group metals.

The Region lies within the wet-dry tropics and has a distinct monsoon-like climate. Virtually the entire rainfall occurs in the Wet season, which varies in length but is generally confined to the November–March period; October and April tend to be transitional months; with the Dry season lasting from about May to September. Annual rainfall at Jabiru (12°40'S, 132°54'E) has averaged approximately 1450 mm over the past 20 years and evaporation exceeds rainfall in most years. Prevailing winds are easterly to south-easterly in the Dry season and northerly to north-westerly in the Wet season, and, like other parts of northern Australia, the Region is subject to cyclones.

The two major river systems of the Region, the East and South Alligator rivers, both drain to Van Diemen Gulf and are tidal in their lower reaches. The headwaters of these rivers and their major tributaries rise in the sandstone plateau region to the east and south and generally flow in a north-westerly direction in shallow valleys across the lowlands to discharge through extensive flood plains. The upper sections of tributary streams usually have sandy or rocky bottoms, and in places are bordered by dense vegetation. The stream courses in the lowlands vary in form, but most commonly they are channel complexes which link billabongs. In the Wet season they overflow into adjacent swamps.

The three Alligator rivers and the Wildman River maintain a flow in their lowest sections in the Dry season. All other streams - including the main tributaries, Cooper, Magela, Nourlangie, Jim Jim and Barramundie creeks - cease to flow for the major part of their length in the last few months of most Dry seasons. Permanent water is restricted to springs, waterholes and billabongs.

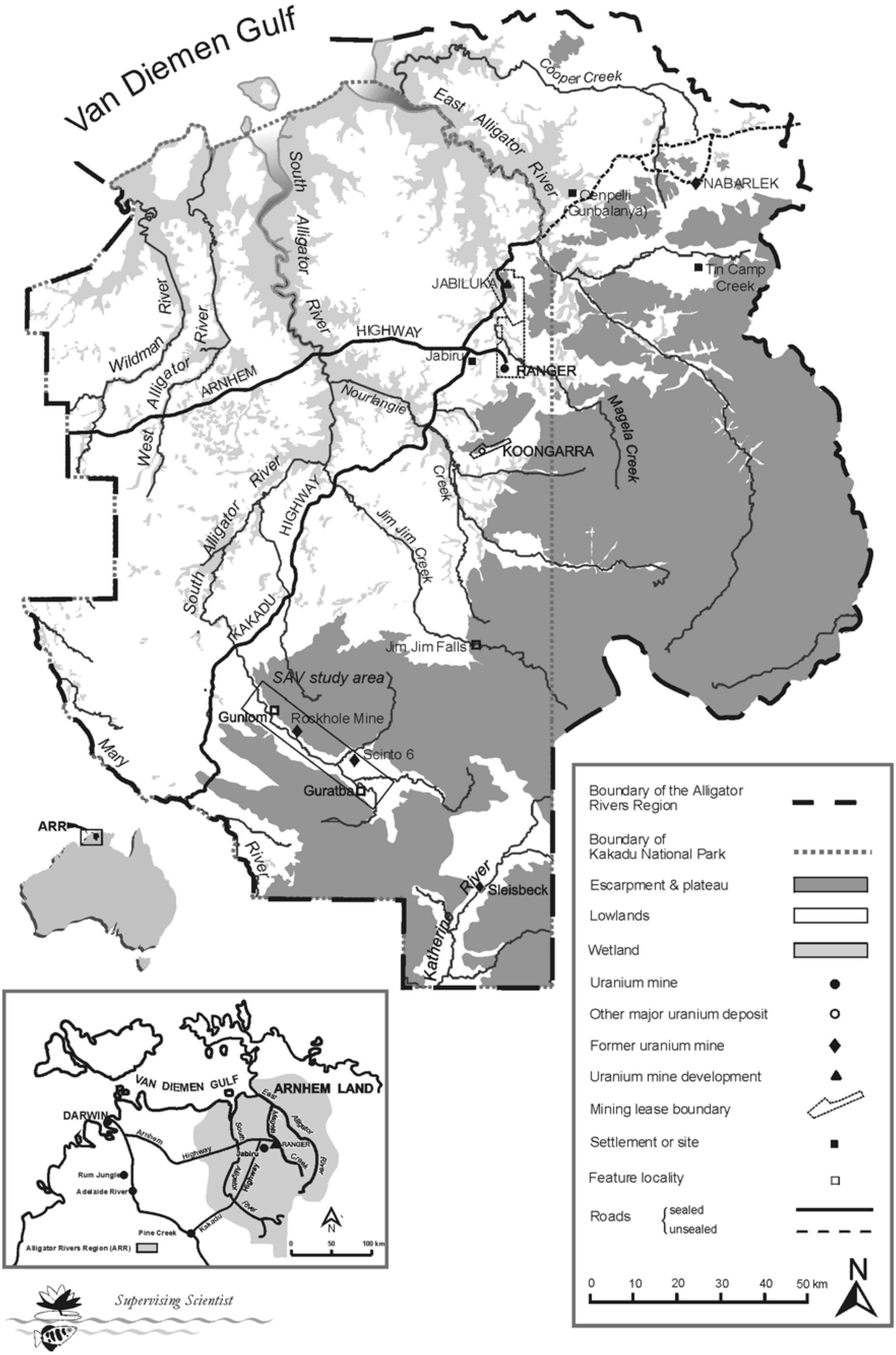

Figure 1 The Alligator Rivers Region in Australia's Northern Territory. The boundary of Kakadu National Park, within the region, is indicated.

The major rivers maintain their channels and levee banks across the flat floodplain areas. Some of their major tributaries (eg Magela Creek) are cut off from the river by a levee bank and require an accumulation of Wet season water before commencing to flow into the river. Thus a flood plain, or more accurately a backwater plain, is formed. These broad areas of flooding remain for periods varying from three to nine months according to location and rainfall. Once this water has receded there remain only permanent billabongs on a dry plain; these are extremely important for the maintenance of the ecosystems.

The hydrological regime is dictated by the seasonal rainfall distribution and both the total annual stream discharge and its pattern within a season can vary considerably. Wet season stream flows typically comprise a series of peak flows superimposed on a base flow which usually begins in about mid-December and ceases by the end of June. In a wet year, however, flow might commence in November and finish in August. The flow pattern over this period varies considerably from year-to-year; eg the total annual flow past GS8210009 in Magela Creek near Jabiru East was recorded as approximately 840 million cubic metres in 1975–76 and 190 million cubic metres in 1982–83, and between 1972 and 1986 the number of days of flow in any one season ranged from 82 to 170.

The distinctive subregions and the large seasonal changes give rise to a wide diversity of plant and animal habitats. The Region is rich in numbers of species of both flora and fauna. Zoologically and botanically it is representative of a large part of the far north of tropical Australia but because of the diversity of the native species that occur in the Region, it is regarded as one of the richest in Australia in biological terms. For example, almost 1500 species of plants have been recorded and they occur in a wide range of vegetation types, including mangrove, grassland, monsoon forest, woodland and scrub communities. More than one-third of the bird species in Australia have been sighted in the Region, and the large populations of waterbirds on the wetlands are one of its outstanding features. Of the aquatic fauna, the fifty species of fish occurring in the Region represent about a quarter of all recorded Australian native freshwater fish.

2.2 Early mining in the Region

The region is within an ancient geological basin called the Pine Creek Geosyncline which has a long history of mineral production. Uranium exploration in the Geosyncline was stimulated by the discovery in 1949 of secondary uranium mineralisation near Rum Jungle, south of Darwin. This was followed by a decade of intense exploration activity resulting in the discoveries of economic uranium orebodies at Rum Jungle and in the upper reaches of the South Alligator River valley.

Exploration and mining activity in the South Alligator River valley in the 1950s and 1960s resulted in the discovery of minor gold, silver, lead, zinc and iron in addition to significant uranium deposits (some of which contained recoverable gold). The South Alligator River valley uranium field was small, containing thirteen now worked-out mines (total production 874 tonnes U_3O_8) and over fifteen prospects, mostly within a north-west trending belt 24 km long and 3 km wide, located about 220 km south-east of Darwin (Fig 1).

In 1953, following the Rum Jungle discoveries, a program of examining base metal prospects for signs of radioactivity led to the discovery of the Coronation Hill uranium ore body. This mine commenced operations in 1956 and ceased in 1964; 75 tonnes U_3O_8 were produced in that period.

In the same year as the Coronation Hill discovery, radioactivity and mineralisation were discovered at Sleisbeck near the Katherine River, some 50 km to the south-east. This ore was mined by open-cut and gloryhole in 1956. Production was below expectations totalling only 3 tonnes U_3O_8.

In 1954 further discoveries were made at the Scinto mining claims, the rich El Sherana outcrop, and the Palette and the Saddle Ridge ore bodies. The El Sherana mines proved to be the most productive in the South Alligator field (411 tonnes U_3O_8). Production from these mines was by shallow open-cut and cut-and-fill stoping from small shafts.

By 1957 the reserves developed by testing the Rockhole, El Sherana, Saddle Ridge and Scinto lodes were sufficient to justify small treatment plants. One company, South Alligator Uranium NL, erected a small plant at the foot of the ranges near the Rockhole lode. United Uranium NL took over the gold treatment plant at Northern Hercules (later renamed Moline) 55 km west of the ore bodies and converted it to a solvent-extraction uranium plant. Both plants were operating by 1959.

The widely scattered deposits in the valley with variations in grade, size and continuity, as well as the location on steep slopes contributed to an operation that was complex and relatively short lived. After production ceased in 1964 the mines and associated workings were abandoned. With the exception of the Sleisbeck Mine all lie within a region previously defined as being a Conservation Zone of Kakadu National Park Stage III. Exploration in the 1980s near two of these abandoned uranium mines (Coronation Hill and El Sherana) resulted in the discovery of significant concentrations of gold, platinum and palladium metals.

The Coronation Hill Joint Venture (CHJV) comprising BHP Gold Mines Ltd, Noranda Pacific Ltd and Norgold Ltd commenced exploration and drilling activities in 1986 at the site of the Coronation Hill uranium mine. In 1991, the Commonwealth Government decided that mining at Coronation Hill should not proceed and the Conservation Zone was subsequently re-incorporated into Kakadu National Park.

2.3 Recent mining in the Region

All the known major uranium deposits of the East Alligator River uranium field have been discovered since 1969. Energy Resources of Australia Ltd (ERA) operates the Ranger Mine, 8 km east of the township of Jabiru. The mine lies within the 78 sq km Ranger Project Area (RPA) and is near the Magela Creek, a tributary of the East Alligator River. Following successive declaration in stages, the RPA is now surrounded by, but does not presently form part of, Kakadu National Park. Mining and commercial production of uranium concentrate have been underway since 1981. Mining of orebody No 1 was completed in 1994 while mining of orebody No 3 commenced in May 1997. (The smaller No 2 orebody is close to Mount Brockman, an Aboriginal sacred site, and will *not* be mined.)

Other orebodies discovered in the East Alligator uranium field were located at Nabarlek, about 30 kms east of Oenpelli in Arnhem Land, Jabiluka about 20 kms north of Ranger and Koongarra about 25 kms south-west of Ranger.

The ore at Nabarlek was mined and stockpiled in 1979 and milling took place between 1980 and 1988. The site has been rehabilitated but the operating company, now Hanson Australia Pty Ltd, has not yet been issued with a Revegetation Certificate by the Northern Territory Government that would release it from further responsibility for the site. A number of issues remain to be resolved to the satisfaction of the NT Government, the Northern Land Council and the Supervising Scientist.

In October 1996, Energy Resources of Australia submitted a Draft Environmental Impact Statement (EIS) (ERA, ERA Environmental Services & Kinhill Engineers 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 traditional 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), that 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 wish to proceed with that proposal, a further assessment under the EPIP Act would be required. The Government agreed, however, that any development at Jabiluka that was consistent with both the RMA and the JMA proposals could proceed subject to the normal approval process. ERA subsequently developed the decline at Jabiluka and constructed an Interim Water Management Pond (IWMP) as part of a water management system to ensure ongoing protection of the downstream environment.

In June 1998, ERA submitted a Public Environment Report (PER) (ERA, ERA Environmental Services & Kinhill Engineers 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.

The Koongarra uranium deposit is located 20 km to the south of Ranger. Uranium ore occurs in two distinct but clearly related mineralised bodies separated by a barren gap about 100 metres in length. The ore resource at Koongarra is relatively small (containing some estimated 15 300 tonnes of U_3O_8) and because of its location in the Nourlangie catchment which drains to the South Alligator River, the Ranger Uranium Environmental Inquiry recommended against its exploitation. There are no immediate plans for mining of the Koongarra orebody.

3 Environmental protection in the Alligator Rivers Region

3.1 Environment protection objectives

Before any environmental protection regime can be established, the government's environmental protection objectives need to be specified in a manner that enables regulators to identify criteria against which the adequacy of environmental protection (including the protection of humans) will be judged. Similarly, these criteria are needed by research scientists whose task it is to carry out research on the effects of industrial activity on the environment with the objective of making recommendations on standards, practices and procedures to be adopted by industry for the protection of the environment.

3.1.1 Protection of aquatic ecosystems

The Ranger Uranium Environmental Inquiry (Fox et al 1977) recommended that mining and export of uranium could proceed in the Alligator Rivers Region subject to the adoption of stringent health and environmental standards. While the Inquiry acknowledged the outstanding cultural and natural heritage values of the Region, it also acknowledged that some finite level of detriment would need to be accepted in order for mining to proceed. The problem for regulators and the Supervising Scientist was in specifying a level of detriment that would be acceptable. Very little precedent was available in Australia during the 1970s and 1980s for specifying environmental protection objectives for areas of high conservation value.

As reviewed in Johnston (1994), the approach eventually adopted by the Supervising Scientist was to concentrate on the concept of 'protection' rather than 'detriment'. That is, rather than specifying an acceptable level of 'damage', control measures and monitoring methods were sought that would ensure and demonstrate that the environment has not been harmed and would probably not be harmed by the mining and processing of ores. The Supervising Scientist concluded that the only practical protection target for the highly valued environment of the ARR was that mining operations produce no *observable* biological effect in a suitably defined monitoring program comprising a number of organisms selected from different trophic levels and phyla and using a range of sensitive endpoints.

Since the mid 1990s, this objective has been further refined to take into account nationally-accepted principles and benchmarks for conserving the nation's natural heritage. (Notwithstanding, an important feature of the Supervising Scientist's original objective that is preserved in current ARR and national objectives is the expression of such management goals in terms of ecological criteria.) In particular, two important national developments have led to refinement of the ARR objective:

- The *National Strategy for Ecologically Sustainable Development* (ESD Steering Committee 1992), and two tenets in particular, (i) the precautionary principle, and (ii) conservation and maintenance of biological diversity; and
- Revision of the Australian and New Zealand water quality guidelines (ANZECC & ARMCANZ 2000).

As recommended in the new Water Quality Guidelines — and now accepted by ARR stakeholders — management goals associated with assessment of impact at sites of high conservation value should be couched around the objective of *no change*[1] *to key indicators of biological diversity*[2]. An important distinction between the earlier Supervising Scientist definition and the new objective is measurement criteria now linked to 'important' ecological changes, as opposed to any biological change such as, for example, sublethal responses measured in bioassays (see footnote 2). Associated with such a management goal for ecosystems of high conservation value are the following principles (ANZECC & ARMCANZ 2000):

i. Statistical decision criteria for detecting a change should be ecologically conservative (see footnote 1).

ii. Adopting a precautionary approach, management action should be considered for any apparent trend away from a baseline, or once an agreed threshold has been reached.

iii. Any decision to relax the physical and chemical guidelines for these ecosystems should only be made if it is known that such a decline in water quality will not compromise the objective of maintaining biological diversity in the system. Therefore, considerable biological assessment data would be required for the system in question, including biological effects data and an ongoing monitoring program based on sufficient baseline data.

iv. Where there are few biological assessment data available for the system, the management objective should be to ensure no change in the concentrations of the physical and chemical water quality variables beyond natural variation.

3.1.2 Protection of human health

One of the occupational hazards present at a uranium mine is ionising radiation. Workers at the mine or mill will be exposed to ionising radiation as a direct consequence of their employment due to a combination of external irradiation (predominantly by gamma rays), and the inhalation of radioactive dusts and radon progeny. Basic occupational hygiene ensures that the ingestion of radionuclides is a negligible radiation exposure pathway.

Furthermore, uranium mining and milling activities are a source of radiological exposure for people in the surrounding region. Radon, radon progeny and radioactive dusts are carried by wind away from the minesite and may be inhaled by members of the public. Radionuclides from the minesite which enter rivers or creeks may be ingested by people who use the waterway as a source of food or water.

The International Commission of Radiological Protection (ICRP) has developed a system of radiological protection which applies to both occupational exposure and the exposure of members of the public. In general terms, the ICRP states that 'The primary aim of radiological protection is to provide an appropriate standard of protection for man without unduly limiting the beneficial practices giving rise to the radiation exposure.' (ICRP 1990). This aim is embodied in the three principles of the system of radiological protection developed by the ICRP (1990), viz:

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1 'No change': In practice and in the absence of information that would define the thresholds of ecological change, refers to statistically conservative changes from a baseline mean or median value, eg change of 10% or one standard deviation, or trend away, from a baseline mean.

2 Changes to: species richness, community composition and/or structure; species of high conservation value or species important to the integrity of ecosystems; or, ecosystem processes of a physical, chemical or biological nature.

1. No Practice involving exposures to ionising radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes. (The justification of a practice)
2. In relation to any particular source within a practice, the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures where these are not certain to be received should be kept as low as reasonably achievable, economic and social factors being taken into account. This procedure should be constrained by restrictions on the doses of individuals (dose constraints), or the risks to individuals in the case of potectial exposures (risk constraints), so as to limit the inequity likely to result from inherent economic and social judgements. (The optimisation of protection)
3. The exposure of individuals resulting from the combination of all the relevant practices should be subject to dose limits, or to some control of risk in the case of potential exposures. These are aimed at ensuring that no individual is exposed to radiation risks that are judged to be unacceptable from these practices in any normal circumstances. Not all sources are susceptible of control by action at the source and it is necessary to specify the sources to be included as relevant before selecting a dose limit. (Individual dose and risk limits).

Thus the objective is to ensure that radiation exposures only occur if justified, and then are As Low As Reasonably Achievable (the ALARA principle) *and* below dose limits. The dose limits, which are summarised below, exclude radiation exposure from natural background radiation or from medical procedures.

Type of exposure	Dose Limit
Occupational	20 milli Sieverts per year, averaged over defined periods of 5 years with a maximum dose in a single years of 50 milli Sieverts
Public	1 milli Sievert per year

3.1.3 Rehabilitation of mine sites

The original Environmental Requirements (ERs) were not specific about the standards to be achieved for rehabilitation at mine sites in the ARR. To rectify this, the Commonwealth and Northern Territory Governments, following extensive discussions between Parks Australia and the Northern Land Council, agreed in 1990 upon the Goal and Objectives for Rehabilitation at Ranger. In 1999, the Ranger ERs were revised by the Commonwealth following discussions with the Northern Territory government and the Northern Land Council. These revised ERs now specify that the goal of rehabilitation at Ranger is to establish an environment similar to the adjacent areas of Kakadu National Park such that, in the opinion of the Minister with the advice of the Supervising Scientist, the rehabilitated area could be incorporated into the Kakadu National Park.

The ERs go on to specify three major environmental objectives of rehabilitation at Ranger are:

1. revegetation of the disturbed sites of the Ranger Project Area using local native plant species similar in density and abundance to those existing in adjacent areas of Kakadu National Park, 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;

2. stable radiological conditions on areas impacted by mining so that, the health risk to members of the public, including traditional owners, is as low as reasonably achievable; members of the public do not receive a radiation dose which exceeds applicable limits recommended by the most recently published and relevant Australian standards, codes of practice, and guidelines; and there is a minimum of restrictions on the use of the area; and

3. erosion characteristics which, as far as can reasonably be achieved, do not vary significantly from those of comparable landforms in surrounding undisturbed areas.

The ERs for Jabiluka, originally specified in 1982, have not yet been revised. However, under an agreement between the Commonwealth and Northern Territory governments (dated 17 November 2000), the Northern Teritory has agreed to revise the Jabiluka ERs to ensure that they are similar to the revised Ranger ERs. For this reason, the Jabiluka Minesite Technical Committee, in assessing the annual plan of rehabilitation for Jabiluka, has been working on the premise that the above goal and objectives for rahabilitation for Ranger apply to Jabiluka.

The goal for revegetation at Nabarlek, agreed between the Northern Land Council and Queensland Mines Ltd is:

> to produce a self-sustaining woodland community which will blend in with the surrounding environment as well as adequate cover of ground species.

This is reflected in the operating company's stated objectives for its revegetation program which are:

1. long-term surface stabilisation

2. maintenance of an appropriate water balance in the area

3. establishment of woodland communities which will blend in with the surrounding environment

3.2 Rehabilitation of disturbed landscapes

Effective and sustainable rehabilitation of severely disturbed landscapes, as at minesites, is a significant scientific challenge both in Australia and overseas and, despite the rhetoric, is not achieved other than at some strip-mined mineral sands and bauxite operations. Research on natural systems rarely provides a basis for tackling the concepts and developing the strategies needed to deal with the substantial disturbances at hard-rock mines in order to reconstruct landforms, hydrological processes and ecosystems that can function in a predictable and sustainable fashion in concert with climate and earth-surface processes in the local region. Mobilising multi-disciplinary scientific and technical skills in order to make progress in this field is yet another challenge.

For this reason a large number of studies have been carried out on the waste rock landforms at Ranger and the surrounding landscapes by both ERA and ***eriss***. ERA and EWL Sciences have concentrated on the waste rock landforms because these will form the foundations of the final landscapes (above grade structures; cappings on tailings-filled mine pits) in the rehabilitated minesites. Investigations thus far can be generally subdivided into:

- the characteristics of the rock materials and the incipient soils forming from them;
- the geotechnical properties of the materials forming the landforms;
- the internal structure of the landforms;
- hydrology and seepage characteristics;

- surface form and erosional behaviour;
- revegetation and ecosystem reconstruction;
- the behaviour of sentinel wetlands; and
- monitoring systems and strategies that measure success.

As well, there has been extensive investigation of issues relating to the storage and consolidation behaviour of tailings.

ERA's primary objective is to establish the basis for constructing landforms and ecosystems that behave and evolve in a predictable manner consistent with the rehabilitated Ranger and Jabiluka minesites being managed in the same way as the surrounding areas of Kakadu National Park. Because of uncertainties in the Ranger mine plan and the development of Jabiluka, it is not yet possible to be definite about the design of the final landforms at Ranger. However, conceptual designs being developed for the landforms and specific designs for target habitats and ecosystems are now being presented to stakeholders for discussion.

3.3 Key issues for research

An issue that always arises in the planning, conduct and reviewing of research carried out on the impact of mining in the ARR is that of deciding the most appropriate structure for the description of the program.

There are a number of logical approaches that could be followed. For example, one approach is to follow a pathway analysis. Thus, the pathways by which offsite environmental impact could occur are by surface water transport, groundwater transport and atmospheric dispersion. Each of these pathways can then be examined in detail to determine their principal components and in this way a logical structure for the program can be defined.

An alternative approach is one based on time scale. Thus, research in the ARR can be categorised into baseline research, research on the impact of mining during the operational phase of mining, and research on the impact of mining during and following rehabilitation. The latter approach was adopted at ***eriss*** during the 1990s; for details see Figure 4 of Johnston (1994).

Experience has shown that, no matter which approach is adopted, anomalies occur. For example, in the time scale approach, erosion and hydrology research was included in the rehabilitation phase because the principal issue being addressed was erosion of rehabilitated landscapes. But environmental protection issues related to erosion also arise during the operational mining phase. Similarly, if one adopts the pathway analysis approach, a number of water issues relate both to surface water and to groundwater transport.

For these reasons, we have chosen to use a hybrid approach in this review and to specify a number key issues on which research has been, and in many cases continues to be, required to ensure protection of the environment throughout the operation of a mine and following rehabilitation. These key issues, which determine the structure of the remainder of this review are:

- Baseline research
- Surface water management
- Dispersion in groundwater
- Atmospheric dispersion

- Rehabilitation
- Revegetation

Note that, in the above list, revegetation aspects of rehabilitation have been separated from the physical issues such as surface hydrology, erosion and the dispersion of erosion products.

The research carried out by ***eriss*** and ERA/EWLS on these issues is described in chapter 5.

4 Strategic roles of organisations

Historically, research on the environment of the ARR began in the 1970s under the leadership of the then Australian Atomic Energy Agency (AAEC now ANSTO). This was in the form of a joint government-industry Environmental Fact-finding Study of the ARR to collect the information necessary to describe the environment of the Region. The impetus for this study was the discovery (see section 2.3) of significant orebodies at Ranger, Jabiluka, Nabarlek and Koongara and the study was a precurser to the Ranger Uranium Environmental Inquiry.

Following the Australian Government's decision in 1977 to proceed with the mining of uranium in the Region, the principal organisations responsible for the conduct of research in the region have been ***eriss***, Parks Australia (PA), Pan Continental Mining (prior to the sale of Jabiluka) and Energy Resources of Australia (ERA).

The strategic direction of research undertaken by Parks Australia is the optimisation of the management of the cultural and natural values of Kakadu. It does not carry out research on the impact of mining on the environment of the region.

The strategic direction of the ***eriss*** mining related research program is to provide advice on the protection and management of the Alligator Rivers Region to ensure that the region is protected to the standard demanded by the Australian community.

The ***eriss*** mining related program focuses on:

- developing and validating methods and models to measure impact of mining on people and ecosystems, and
- developing standards, practices and procedures for the protection of the environment from the effects of mining.

The strategic direction of the ERA research program is to apply site-specific best practical technologies to the mining operations at Ranger and Jabiluka.

The ERA program focuses on:

- efficient operation of the mining operation,
- rehabilitation of mining operations and disturbed ecosystems,
- protection of the local and regional environment,
- protection of the workers and the general public,
- identification of future land use operations that are compatible with the ecology of Kakadu and the desires of Aboriginal people.

It is clear that the research programs of ERA and ***eriss*** have different focal points. The ERA program is focussed on mine management issues but it has a significant emphasis on how management practices could affect the environment. The ***eriss*** program focuses on the development of, and provision of advice on, methods for assessing and controlling environmental impact.

There are areas in the two programs where there is no overlap of role and therefore no overlap in research. For example, ERA carries out research on mine production and management practices to minimise water and tailings storage requirements. This is a commercial issue and ***eriss*** has no role in it. On the other hand, ***eriss*** carries out research on which to base recommendations to the regulatory authority on environmental protection standards; for example, radiological standards for the discharge of waters from the mine site. Being a regulatory issue, it would not be appropriate for the mining company to make such recommendations.

In other areas there is a commonality of interest but not of role. An example is research on the shape and structure of the final landform to minimise erosion. The ***eriss*** role in this case is to develop methods and models by which the long-term development of the landform through erosion processes can be estimated, primarily to ensure that tools are available to assess possible off-site impact. The ERA role is to optimise its landform design both to ensure cost-effective construction and to achieve best practice in protecting the environment. That is, the output of ***eriss*** research in this case can be viewed as a design tool for the mining company. Similarly, in the field of regional environmental research, ERA's program includes studies on regional ecological issues that relate back to the mine site; for example, research on fire management strategies that could be applied to rehabilitated areas of the mining lease. ***eriss***, on the other hand, carries out research on regional issues that can be used to make recommendations on biological monitoring programs that should be carried out by mining companies and to provide managers of wetlands with the information that they need.

There are issues, however, in which both organisations have a legitimate interest and role. These are usually issues that arise at the boundary of the mine site and the off-site environment. An example is the treatment of waters to protect the off-site environment. Constructed wetlands have been used as a method of treatment. Such filters are constructed by the mining company on its lease and their operation is clearly the responsibility of the company. As a method of protecting the environment, however, assessment of the effectiveness of wetland filters could clearly be a legitimate responsibility of ***eriss***. Whether or not ***eriss*** plays a significant role in cases like this will depend on a number of factors including the availability of resources, the expertise required (although this can be provided via consultancies if not available at ***eriss***) and the desirability of having independent advice based on research of the Institute. The Technical Committee has a role to play in such decision making.

The NT Department of Business, Industry and Resource Development (DBIRD, incorporating the former Dept of Mines and Energy, DME) is the regulator of uranium mining in the Alligator Rivers Region. DBIRD does not have a formal research program into the effects of mining on the environment of the region but it conducts specific investigations on an *ad hoc* basis as required. DBIRD requires the operators of mines under its jurisdiction to carry out environmental monitoring programs and it formally reviews the results of these programs. DBIRD publishes a six monthly report on the results of these monitoring programs in the ARR and presents this report to the Alligator Rivers Region Advisory Committee.

5 Overview of research in the ARR 1978–2002

5.1 Baseline research

The broad objective of baseline research in the Region has been to document relevant physical, chemical and biological characteristics of the environment of the Region unaffected by contemporary mining.

Baseline research has been necessary for two main reasons. First, little was known about the ecosystems of the ARR before approval for modern mining given in 1977. Given that the principal aim of the environmental protection program is to ensure that local ecosystems are not harmed, it was essential that adequate baseline knowledge of the ecosystems be established before appropriate environmental protection measures could be recommended. Second, in the development of specific measures for environmental protection and surveillance (eg biological toxicity testing and biological monitoring) it is essential that the ecology and biology of the animals and plants used in these programs are properly understood.

The first baseline studies were conducted under a joint government-industry Environmental Fact-finding Study of the ARR was initiated in 1972 to collect the information necessary to describe the environment of the Region. Twelve projects were undertaken studying both natural and cultural aspects of the Region and a series of reports were prepared (ARR Fact Finding Study 1973). These reports contain the record of the first environmental studies in the Alligator Rivers Region. However, much of the work conducted on the flora and fauna of the Region resulted in little more than surveys and species inventories. Moreover, the taxonomy of many groups of organisms surveyed at the time was so poorly understood that the species lists contained a large number of undescribed forms.

Three workshops were organised by the Supervising Scientist in 1978 and 1979 to discuss and formulate, with the advice and assistance of the ‘group of experts’, priorities in a program of research to be conducted in the Region. The first workshop (August 1978) dealt mainly with biological and chemical features of the environment. At the time, it was considered that the major potential environmental impact of the proposed mining operations would be from the release of contaminated mine waste waters. Surface waters are the chief vehicle for transport and dispersion of mine derived wastes and, since aquatic organisms are continuously exposed to wastes, the program formulated from the 1978 workshop (and refined in a subsequent workshop in December 1979) focussed mainly on the aquatic ecosystems of the Region. The remaining workshop dealt with radiological effects on members of the public and it identified transfer of radionuclides to Aboriginal people via their diet as an important study area.

The detailed programs and priorities drawn up at these workshops were largely implemented by the Supervising Scientist, forming the basis of much of the research conducted by eriss in the years 1978- 1985. This program addressed both the biological characteristics of the environment of the Region and the physical/chemical characteristics of the Magela Creek system.

The baseline biological research in the Region, particularly the Magela Creek catchment, has recently been summarised by Gardner et al (2002) as a preliminary step in the establishment of a proposed landscape scale monitoring program. In the first part of the summary, a description is given of the floodplain habitats and of the flora and vertebrate fauna under the headings: vegetation, algae, fish, amphibians, reptiles, birds and mammals and alien species.

The second part of the summary is an annotated review of individual papers and reports presented under similar headings.

No such summary of the physical/chemical baseline research in the region has been prepared. A brief summary of research undertaken is provided below.

Extensive studies of the physico-chemical properties of surface waters of the Magela, Cooper and Nourlangie systems were undertaken by the then NT Water Resources Division, by the mining companies and by ***eriss*** both directly and through collaborative research projects with the University of Tasmania and the Chisholm Institute of Technology. The principal objectives were:

- to obtain a quantitative chemical description of the waterbodies throughout the full annual cycle and hence characterise the principal seasonal variations in water chemistry, and
- to provide a baseline data set of the physico-chemical properties of waterbodies that is sufficient to enable the identification of major changes arising from mining activities.

The above work has been reported in Annual Research Summaries of ARRRI/***eriss*** (ARRRI 1984, 1985, 1987a&b & 1988), in a number of reports in the Supervising Scientist series of publications (Bruton 1982; Hart & McGregor 1982a; Walker et al 1982, 1984; Walker & Tyler 1982) and in the scientific literature (Hart & McGregor 1980; Hart 1980; Kirk & Tyler 1986; Walker 1984; Walker & Tyler 1984).

The chemistry of rainfall in the region was also investigated in some detail primarily to establish the contribution to rainfall acidity arising from the emissions of sulphur dioxide from the acid plant and the electricity generating plant at Ranger. These studies are referenced in the section 5.4 on Atmospheric research.

Hydrological modelling of the Magela Creek and floodplain was undertaken to enable the prediction of the fate of contaminants released into surface waters from the Ranger mine. A daily rainfall-runoff model for Magela Creek was developed by Vardavas (1988). A simple water balance model was developed which uses daily rainfall, averaged over the Magela catchment, and monthly-averaged daily evaporation to predict the daily discharge at the catchment outlet. The monthly evaporation was determined from pan evaporation data and lake-to-pan coefficients obtained using a previously developed evaporation model (Vardavas 1987b). This surface runoff modelling was extended to simulate the water budget of the whole Magela flood plain (Vardavas 1989a, 1989b). The model provided daily estimates of the volume of surface water on the flood plain and the discharge rate at the outlet channel.

Three studies of the mixing zone near Ranger were carried out. These studies used fluorometric dye tracing (Smith et al 1986), examination of water released from RP4 at Ranger (Noller et al in ARRRI 1985, 78), and the use of a tritium tracer (Johnston et al in ARRRI 1987b, 55–61).

Metal speciation in Magela Creek and its significance to the environmental impact of water release was examined in a collaborative study by ARRRI/***eriss*** and the Chisholm Institute of Technology on the following key areas:

- The speciation of metals in mine waste waters and in surrounding natural waters to determine basic speciation properties of these waters (Hart & McGregor 1982, leGras & Noller 1989, Noller & Currey 1983, Noller et al in ARRRI 1987a, 62-70);

- The processes which occur to metals when mine waste waters or specific additions of metal ions are added to natural waters (Hart et al 1983, Hart & Jones 1984d, Hart et al 1984, 1985a, b & c);
- The capacity of natural waters to 'absorb' labile heavy metals (Hart 1981; Hart & Davies 1981, 1984; Hart & Jones 1984a);
- Removal processes in natural waters involving iron and manganese (Hart 1982, Hart & Jones 1984b & c, Noller et al in ARRRI 1984 p29, 1985 pp70–74); and
- Dissolution processes, including those involving iron and manganese, which result in return of labile metals to the water column (Noller & LeGras in ARRRI 1988 pp49–51).

The fate of chemical species in the Magela system was investigated in a number of projects:

- The transport of trace metals and suspended solids in the creek (Hart et al 1982) and a materials budget for the Magela catchment (Hart et al 1987a & 1987b)
- A comparison of the water borne materails budget for a number of key constituents with corresponding loads in macrophytes (Noller 1988) and in Melaleuca litter and grasses (Finlayson et al in ARRRI 1987b)
- More detailed studies of suspended solids material and bottom sediments from billabongs (Davies & Hart 1981; Thomas et al 1981; Thomas & Hart 1984; Hart & Becket 1986, Hart et al in ARRRI 1987a & 1987b).

These studies enabled:

- characterisation of the sources of chemical species including rainfall, runoff and loads in mine waste water ponds;
- establishing loads transported naturally by Magela Creek including an assessment of speciation;
- assessment of the fate of chemical species with respect to deposition as sediment in creek beds, billabongs and on the flood plain itself, the quantities stored in floodplain sediments, recycled in macrophytes, litter and grasses on the flood plain and removed from the flood plain; and
- establishing the detailed physico-chemical properties of particulates and colloidal materials transported by the Magela Creek and in the bottom sediments of billabongs.

5.2 Surface water management

5.2.1 Introduction

Throughout the recent period of mining of uranium in the Alligator Rivers Region, water management has been the single most important issue in mining operations and in research related to mining.

The original water management plan proposed by Ranger in its submission to the Ranger Uranium Environmental Inquiry envisaged that, after the first few years of operation, controlled releases of water from what was then known as the Restricted Release Zone (RRZ) would need to be made to Magela Creek throughout the lifetime of the project. The water management system that was finally adopted and authorised was a modified version of the original plan but direct release of water to Magela Creek remained an integral part of the system. Water management at the uranium mine at Nabarlek, though a self-contained system during its short operational life, envisaged the release of residual waste water during the decommissioning and rehabilitation phase.

For these reasons, extensive research was undertaken to determine appropriate chemical and radiological standards that would ensure the protection of downstream ecosystems and people living downstream from mine sites. At the same time, the fundamental issues of on site water management were investigated to ensure that reliable hydrological models were available to provide a predictive capacity.

Recognising the inherent limitations of control methods based on chemical concentrations alone, programs of research were undertaken to establish a biological regime for the control of direct releases of water from mine sites. This regime was based upon toxicological testing and biological monitoring.

Direct releases of water from the RRZ at Ranger would only have been possible in the later months of the Wet season when suitable flow conditions had been established and the need for release had been clearly established. For this reason, ERA proposed the use of land irrigation during the Dry season as a complementary method to direct release of water during the Wet season. Extensive research was therefore carried out on this method water management.

The direct release of water from the RRZ at Ranger was opposed by the Northern Land Council acting on behalf of the traditional owners. Initially, this opposition led to restrictions being placed on the frequency of such releases by the Commonwealth Government. In 1987, it was decided that direct release could only occur in Wet seasons where the total rainfall exceeded that expected no more often than one year in ten. The Wet season of 1994–95 was one of very high rainfall and an application by ERA to release water from Retention Pond 2 to Magela Creek was approved by the NT Minister and supported by the Commonwealth. The NLC filed an injunction to prevent the release. The injunction failed but ERA, in recognition of the concerns of the traditional owners, decided not to proceed with the approved release. It also decided that it would not submit any future application for the direct release of RRZ water except under trully exceptional climatic conditions.

These developments led to an increased emphasis on land irrigation as the primary method of water management at Ranger and also to the investigation of other methods such as wetland filtration, enhanced evaporation and active water treatment.

In the following sections the scientific investigations on all of the above issues are summarised under the following headings:

- Mine site hydrology
- Control measures for the protection of aquatic ecosystems
- Environmental monitoring and asssessment
- Protection of human health, and
- On-site processes to protect the off-site environment

5.2.2 Minesite hydrology – Ranger

The water management system at Ranger comprises physical structures involved in the collection, storage, treatment and disposal of all waters which come into contact with either the mining or milling aspects of the Ranger project and management procedures.

The physical structures include drains and diversion bunds constructed to control runoff, pumps and piping networks for distributing water within the system. Management procedures are in-place to handle water movements within the system. There are three core components or circuits in the water management system, namely; process water which has to be retained on site (tailings dam, Pit #1and tailings corridor), pond water which can be disposed of by land irrigation (RP2 and Pit #3) and sediment control water which overflows to natural creek systems providing water quality is appropriate (RP1, Corridor Creek constructed wetlands, Djalkmara Billabong and the RP1 constructed wetland).

The water management systems provide a water supply for the operations as well as control mechanisms for minimising potential impacts of the mining operations on downstream ecosystems. Key variables affecting the operation of the water management system include:

- annual rainfall and its distribution (spatial and temporal);
- evaporation rate;
- runoff factor; and
- water usage for the mill and mine.

Process water is confined to the tailings dam and Pit #1 and is currently disposed of by evaporation only. A large inventory has developed in the process circuit partially due to above-average rainfall at the Ranger site in recent years. An innovative treatment technology has been developed involving lime-softening and reverse osmosis and a pilot-scale plant was successfully tested at Ranger late in 2001. The operations of the pilot scale plant are currently being scrutinised in order to generate optimum operational configurations for a full-scale treatment plant (750 000 m^3 throughput per annum).

Pond water is collected from runoff and seepage from the mill and mine areas in Retention Pond #2 (RP2). When the statutory maximum operating level in RP2 is likely to be exceeded, pond water is pumped to Ranger #3 for temporary storage. Pond water is treated and disposed of by wetland filtration and irrigation.

Sediment control water is runoff from non-mineralised stockpiles and natural woodland areas and is collected in RP1, Djalkmara Billabong and the Corridor Creek wetlands. RP1 and the Corridor Creek wetlands overflow during the Wet season whereas Djalkmara Billabong is pumped to Magela Creek in accordance with strict water quality criteria.

Prior to March 2000, minesite waters at Ranger were managed in accordance with a 'Restricted Release Zone' concept which related to the origin of the water. However, since March 2000, new Environmental Requirements require the Company to manage on site waters according to quality.

Substantial research has been undertaken on wetland filtration and, in particular, the manner in artificial wetlands can be constructed to mimic the solute removal processes that characterise natural wetland environments in the region (Jones et al 1995, Jones 1996, Jones & Eames 1997, Buck et al 1997, Payne & Twining 1997, leGras & Klessa 1997, Jones et al 1997, Overall 1998, Jones & Jung 1999, Overall et al 2001, Overall 2001, Markich et al 1999, Jones et al 2000). In addition, more recent investigations have focussed on technological approaches to water treatment, culminating in an innovative technique for treatment of process water (Overall & Blinco 2000, Topp et al 2003).

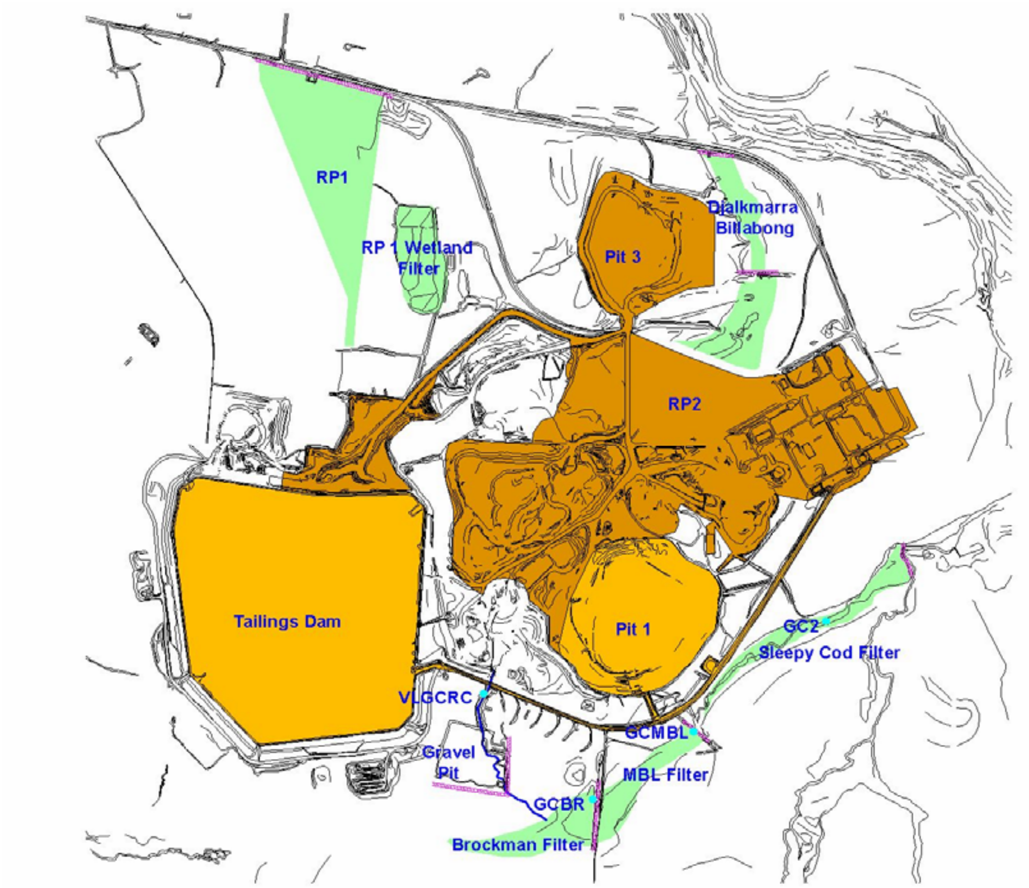

Figure 2 The Water management system at Ranger

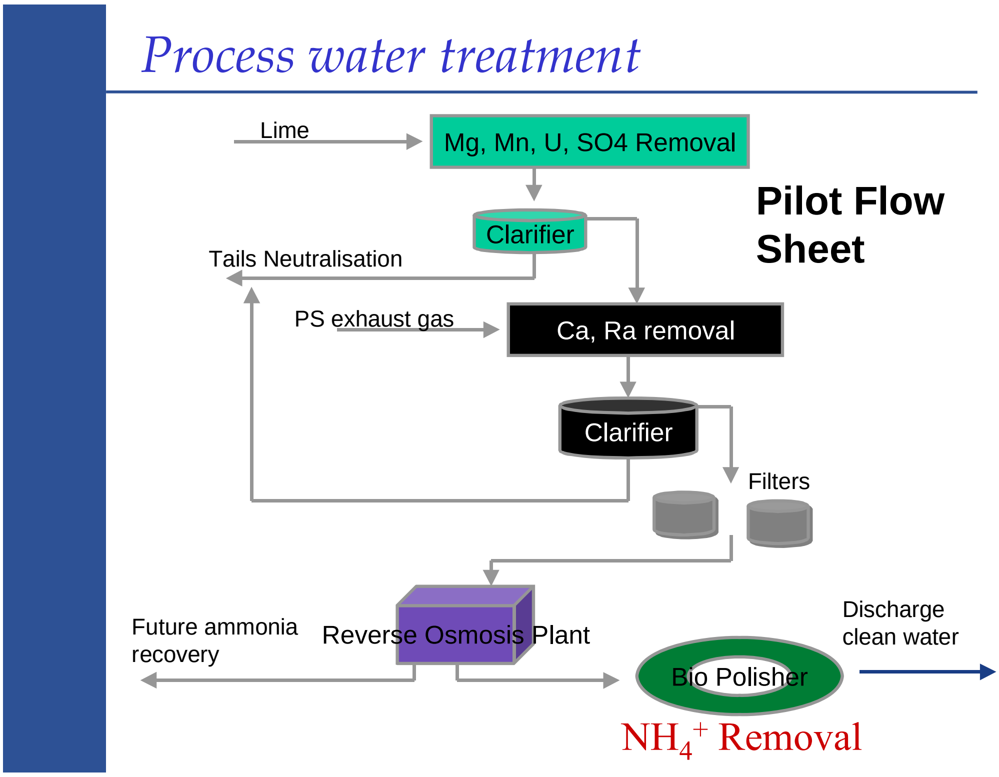

Figure 3 Pilot flow sheet for process water treatment system at Ranger

In terms of limiting runoff and seepage to RP2, recent investigations are being undertaken on capping mineralised stockpiles in order to limit rainfall infiltration and maximise runoff of appropriate quality. Runoff is directed to the sediment control ponds and wetlands and thereby discharged into natural drainage lines over the Wet season.

Recently, a revised water balance model for the Ranger has been developed (ERA 2001). The model utilises catchment information, climatic conditions, wetland/irrigation disposal rates, tailings production and deposition rates and proposed process water treatment rates. Using a monthly time-step over a ten-year period, water movement and storage requirements for each of the three components of the water management system (process water, pond water, sediment control) can be simulated. The modelling process simulates average to extreme Wet seasons using 10 000 Wet season years randomly generated using the Oenpelli rainfall record (1910 to present). Randomly generated rainfall patterns utilise Monte-Carlo techniques. Another phase of development of the water balance model could involve solute concentrations.

5.2.3 Minesite hydrology – Jabiluka

ERA has proposed two alternatives for the development of the Jabiluka Project. The first, known as the Ranger Mill Alternative (RMA) involves the mining of ore at Jabiluka and milling of the ore at the existing mill at Ranger. Ore would be trucked from Jabiluka to Ranger and waste rock would be transported from Ranger to Jabiluka to backfill the mine void at Jabiluka. The second alternative, known as the Jabiluka Mill Alternative (JMA), involves the construction of a new mill at Jabiluka. As originally proposed in the Jabiluka Public Environment Report (PER — ERA, ERA Environmental Services & Kinhill Engineers 1998), tailings produced in the mill would be deposited in two pits excavated on the Jabiluka lease and waste rock would be returned to the mine void. The form of the JMA that received Commonwealth Government approval required disposal of the tailings to the mine void and to specially excavated silos. Waste rock from Jabiluka would be stockpiled at the surface and rehabilitated.

The water management system for the RMA proposal was outlined in some detail in the Jabiluka EIS (ERA, ERA Environmental Services & Kinhill Engineers 1996) while that proposed for the JMA was described in the Jabiluka PER (ERA, ERA Environmental Services & Kinhill Engineers 1998). Both systems were designed on the basis of ‘no release of contaminants’ from the mine site. The design criterion was based upon the concept that the water management system would contain all water even in a Wet season in which the annual rainfall equals that expected no more often than once in 10 000 years. Many aspects of the hydrological modelling used by ERA in the EIS and the PER were criticised by Wasson et al (1998). As a result, a comprehensive analysis of water management issues at Jabiluka was carried out by the Supervising Scientist in his report to the World Heritage Committee (Johnston & Prendergast 1999).

It must be recognised that the hydrological modelling of the Jabiluka Project described by Johnston & Prendergast (1999) did not apply to the actual facility that may be constructed at Jabiluka because, as stated above, the approved project differed from that proposed by ERA and ERA had not yet provided a detailed proposal based on the approval. Nevertheless, the issues assessed and the analysis methods used could be used in the final design of either the RMA or a revised JMA proposal.

In the review of the hydrological analyses carried out by ERA, the Supervising Scientist sought independent advice on hydrometeorology, climate change and hydrological analysis.

These projects are described in detail by Bureau of Meteorology (1999), Jones et al (1999) and Chiew and Wang (1999). The results obtained were summarised by Johnston and Prendergast (1999) and used to develop quantitative risk assessments for ecological and radiological impact.

Some of the more important conclusions of the above research projects were:

- The Oenpelli rainfall record, rather than the shorter Jabiru Airport record, should be used in all hydrological modelling for Jabiluka. (The same conclusion applies to modelling at Ranger.)
- The evaporation pan factors recommended by the Supervising Scientist (Vardavas 1987) and a linear relationship between evaporation and rainfall should be used in all future hydrological modelling.
- The maximum change in annual average rainfall expected from climate change modelling for the Jabiluka region is about 1% over the next 30 years. Hence there is no need to repeat simulation modelling of the Jabiluka water management system to take into account climate change.
- Stochastic hydrological modelling of the Jabiluka system should include simulated distribution of monthly rainfall rather than on an annual basis, a daily water balance rather than a monthly balance and the use of a conceptual rainfall-runoff model rather than fixed runoff coefficients.
- Pond evaporation should be used rather than enhanced evaporation in the ventilation system. In addition, ERA should consider partitioning of the pond into three or four compartments to enable control of evaporation.

The hydrological issues described above were assessed by the Independent Science Panel (ISP) of ICSU. The ISP, in its first report, was generally satisfied with the approach adopted but raised a number of issues. It recommended:

- Increasing design rainfall values by 5% to take into account possible errors in recorded rainfall arising from evaporation and wind effects
- Rainfall and class A pan evaporation measurements should be commenced at Jabiluka as soon as possible
- The predictions of climate change from observations and atmospheric models should be kept under review during the life of the mine and the design of the retention pond area should enable the storage to increase to accommodate a predicted increase in runoff should this be necessary
- The runoff coefficients used by Chiew and Wang (1999) in the runoff modelling should be validated on the basis of hydrological measurements from the Ranger site. The runoff models should be modified if necessary
- an assurance should be obtained that the uncertainties in relation to water requirements at the mill, effluent disposal routes etc have been adequately dealt with in the design of the water management system.

A number of these issues were subsequently clarified. Rainfall and evaporation measurements have been underway at Jabiluka for some years but the record was so short that it had not been used in the analyses. The runoff coefficients used in the analyses had been derived from experience at the Ranger site. It had been planned that climate change analyses would be kept under review by the Jabiluka Minesite Technical Committee. Water requirements at the Jabiluka mill were clarified.

The only outstanding issue was the proposal to increase the rainfall record by 5%. This recommendation was eventually accepted but it was noted that it would be inappropriate to apply this recommendation at Ranger where water balance models have been calibrated. In such circumstances, other changes would be required, for example in runoff coefficients, to return the models to a state of balance.

Issues that should be addressed for the current water management system at Jabiluka include:

- Formally addressing the question of partitioning the current water management pond at Jabiluka as requested by the ISP
- Carry out a quantitative risk assessment for the current water management system at Jabiluka, and
- Review the information on climate change to ensure that no significant change occurs in the conclusions drawn by Johnston & Prendergast (1999).

5.2.4 Control measures for the protection of aquatic ecosystems

The regime proposed by the Supervising Scientist for the control of water release from mine sites (described in eg Johnston (1991, 1994)) has three components:

- Control measures before and during releases to ensure protection of aquatic ecosystems
  - Research on these issues is described in this section
- Control measures before and during releases to ensure protection of humans
  - Described in 5.2.6, and
- monitoring programs during and after releases to assess the adequacy of the control measures
  - Described in section 5.2.5.

The primary objectives of the research program on the protection of aquatic ecosystems are:

- to develop, refine and utilise techniques to assess the risk to aquatic ecosystems associated with the discharge of waste water from mine sites into surface streams.
- to devise or recommend measures, including standards, to regulate such discharges so that the aquatic ecosystems of the Region are not harmed.

The approach initially adopted by ***eriss*** was to develop water quality standards for the Region based on chemical constituents and then, recognising the deficiencies of control measures based solely on chemistry, to develop a set of ecotoxicity tests appropriate to the Region that could be used to specify the dilution of waste water required to protect aquatic organisms (whole effluent testing). This approach, described in Johnston (1994), is still relevant today, the procedures being used to revise standards and being applied to the control of water releases. For either of the approaches, chemical or ecotoxicological, the aim has been to achieve the environmental protection objectives outined in section 3.1.1.

Protection of ecosystems based upon water quality standards

Brown et al (1985) describe in some detail the approach adopted by the Supervising Scientist in deriving standards based upon the natural distribution of concentrations in local streams.

The elements of this approach, culminating in published standards in 1985 (Supervising Scientist 1985), were:

Hazard assessment: Identification of the constituents of water to be considered was based upon the list of elements and compounds for which the USEPA gives water quality standards or which it recommends for inclusion in the development of water quality standards, together with data on the constituents present and enhanced in the local ore bodies.

Derivation of preliminary standards: This was based on a conservative addition to natural concentrations of constituents observed in receiving waters. It was assumed that a change of 10% in the frequency of occurrence of concentrations of any constituent between the 2.5 and 97.5 percentiles of the natural distribution of that constituent would not lead to unacceptable changes in the environment.

Identification of critical constituents: Under scenarios of hypothetical mine waste water releases, constituents estimated to exceed the preliminary standards at Ranger and Nabarlek were identified (ie SO_4, U, Mg, Mn, Ca, NH_3, NO_3). Toxicological data were collected from scientific literature for all these constituents. The toxicity of uranium to local species was assessed in a series of experiments conducted by ***eriss***.

Loads of particular constituents: In addition to these considerations of concentrations in the water column, an assessment was made of the effects of increased loads of the nutrients SO_4, NO_3 and PO_4. Also, the recommendations on annual loads of radionuclides and metals were derived on the basis of a different criterion involving an assessment of the risk to human health.

The new water quality guidelines developed for Australian and New Zealand ecosystems (ANZECC & ARMCANZ 2000) describe procedures to be used in the development of guideline or 'trigger' values for aquatic ecosystems. For ecosystems of high conservation value, development of site-specific trigger values is recommended. The philosophy behind trigger value derivation and application for these ecosystems may be summarised:

> For naturally-occurring physical and chemical variables, background or reference concentrations should not be exceeded unless a locally-derived 'trigger value' based upon local ecotoxicological effects data is available.

Specific guidance on derivation of the trigger value is:

- In the case of reference concentrations, 'no change' in a practical sense refers to a statistically conservative change from a reference median or mean value, ie the 80th percentile of reference data or one standard deviation from a reference mean.
- Where ecotoxicity data are used to derive toxicant trigger values (ie the basis of derivation of published water quality guideline values), a new statistical distribution method is used whereby ecotoxicity data are fitted to a distribution curve to protect a chosen percentage of species; for sites of high conservation value, 99% of species is recommended. This contrast to earlier or alternative (and least preferred) methods of guideline derivation where an (arbitrary) assessment factor is simply applied to the lowest ecotoxicity value

It is interesting to note that these recommendations were, for the most part, adopted for the derivation and application of chemical standards in the ARR more than a decade before their publication by ANZECC and ARMCANZ (2000).

The Environmental Requirements for Ranger were also revised in 2000 (Supervising Scientist 2001). This revision led to a re-assessment of the existing standards including a critical examination of the quality of baseline chemical data (Klessa 2000). New trigger values were derived (Klessa 2001a) on the following basis:

- Three trigger levels are set in accordance with the distributional properties of baseline data from which they are derived, ie 'focus', 'action' and 'limit' levels.
- For normal distributed baseline data, and with the exception of pH, trigger levels are +1, 2 and 3 standard deviations (σ) from the mean, corresponding to 'focus', 'action' and 'limit' levels respectively. In the case of pH, trigger levels are ±1, 2 and 3σ from the mean.
- For non-normal distributed baseline data, trigger levels are the 80^{th} percentile ('focus'), the 95^{th} percentile ('action') and a maximum ('limit') which in the case of U is a site-specific, ecotoxicologically based value (see following section).
- Triggers for ^{226}Ra are based on human health considerations.

Thus, apart from uranium, standards for 'critical constituents' above have reverted to conservative trigger values based upon the distributional properties of baseline data. Conductivity, however, is used as a surrogate measure for Mg and SO_4; this is an interim approach until local ecotoxicological data are gathered for these constituents.

Early derivation of standards based upon local toxicity data focused on data acquired for uranium (ARRRI 1985). At the time this work was undertaken, the best-available approach to trigger value derivation was the assessment factor method in which an assessment factor is applied to the lowest ecotoxicity value. The new water quality guidelines (ANZECC & ARMCANZ 2000) classify trigger values derived using the assessment factor method as 'low reliability'. A new statistical distribution method is recommended to derive 'high reliability' values. In this method, ecotoxicity data are fitted to a distribution curve to protect a chosen percentage of species; for sites of high conservation value such as Kakadu National Park, protection of 99% of species is recommended.

To derive a 'high reliability', site-specific trigger value for uranium, chronic toxicity data for at least five local species from at least four taxonomic groups are required. Such data for the ARR have been acquired gradually over the period ~1990 to the present. Using the statistical distribution method, the site-specific trigger value (to protect 99% of species) for uranium was 5.8 µg L^{-1}. This value is less than the historical site-specific standard recommended by the Supervising Scientist (1985) for Magela Creek of 10 µg L^{-1}, and is about two orders of magnitude above natural background concentrations. The new site-specific value (5.8 µg L^{-1} , van Dam 2002) has now been adopted as a water quality 'limit' for Magela Creek downstream from Ranger.

Similar ecotoxicological work is currently underway at ***eriss*** to derive site-specific trigger values for magnesium and sulphate, the other major constituents associated with Ranger mine waste waters. Laboratory ecotoxicity data are being gathered for similar modelling and trigger value derivation as has been undertaken for uranium. In addition, field mesocosm investigations are also being employed in which natural macroinvertebrate communities in Magela Creek are being seeded in large plastic tubs in the creek channel into which stock solutions containing various $MgSO_4$ concentrations will be spiked. Thus the study will result in laboratory- and field-determined thresholds of tolerance of local organisms to this mine contaminant.

Protection of ecosystems based upon ecotoxicology

The use of local aquatic species for toxicological assessment of chemical contaminant impacts at particular sites is an approach that has been promoted and used in increasing industrial situations in Australia (ANZECC & ARMCANZ 2000, van Dam & Chapman 2001). This approach was adopted as part of the environmental protection program for Ranger in the mid 1980s and the rationale as well as history of ecotoxicity developments at ***eriss*** were extensively reviewed by Johnston (1991, 1994). Toxicity tests for at least 10 local species have been developed since this period with five local aquatic species regularly used for toxicity testing purposes (table 1). With the exception of the fish sac-fry survival test, all the test endpoints represent chronic responses.

Table 1 Current suite of site-specific toxicity tests using species local to the Alligator Rivers Region

Test organism	Duration (acute/chronic)	Test endpoint	Reference
Chlorella sp. (green alga)	72 h (chronic)	Cell division rate	Franklin et al (1998)
Lemna aequinoctialis (duckweed)	96 h (chronic)	Growth (frond number)	Riethmuller et al (in prep)
Moinodaphnia macleayi (water flea)	3 brood (chronic)	Reproduction	Hyne et al (1996)
Moinodaphnia macleayi (water flea)	48 h (acute)	Survival	OECD (1999)
Hydra viridissima (green hydra)	96 h (chronic)	Population growth	Markich & Camilleri (1997)
Mogurnda mogurnda (purple-spotted gudgeon)	96 h (acute)	Larval sac fry survival	Markich & Camilleri (1997)

The ***eriss*** ecotoxicity laboratory was registered by the National Association of Testing Authorities (NATA) for 4 years (1991–94) with the *Mogurnda*, *Hydra* and *Moinodaphnia* tests accepted as fully registered tests. (***eriss*** was the first laboratory in Australia to be registered for such tests.) Staff reductions and turnover led to a decision not to maintain NATA registration due to the high level of laboratory maintenance required. However, all the critical QA/QC regulations put in place during NATA registration have been retained by the laboratory, and it continues to operate to a very high standard.

These and other species have been used to determine water quality guideline trigger values, as described above, and waste water release dilutions through direct toxicity tests (whole effluent testing).

Local species toxicity tests are used to directly assess the toxicity of some mildly-contaminated Ranger waste waters prior to their release into Magela Creek during the Wet season. This procedure is applied because there are deficiencies in the sole reliance upon chemical standards, namely (Johnston 1994):

1. Chemical wastes can be complex in their toxic properties, and regulation by chemical analysis does not always ensure protection of the environment. This is due, in part, to the difficulty of identifying each of the large number of toxicants that may be present in a complex effluent, and also to the lack of toxicity data (concentration-response relationships) for many potentially toxic compounds.
2. It is not possible, using chemical-specific testing methods, to account for the additive, synergistic and antagonistic effects that occur when large numbers of potentially toxic chemicals are mixed in a given receiving water.

Since the mid 1990s, routine toxicity testing of Ranger Retention Pond 4 and/or Djalkmara Billabong waters was undertaken by Ranger's Environmental Division, with an informal supervisory role by ***eriss*** (Humphrey et al 1999). Following the Commonwealth Government decision in 2000 that the Supervising Scientist should carry out a routine environmental monitoring program and the subsequent rationalisation of ERA and SSD activities, ***eriss*** now carries out this work. The dilution of the whole waste required to render it harmless is used as a control parameter to regulate its discharge. In practice, the toxicity of the waste water to three of the species shown in table 1 is assessed. To calculate a 'safe' dilution ratio for the water, the NOEC (No Observed Effect Concentration) of the most sensitive of the species is divided by a safety factor of 10.

Technique development has continued in this field. In particular, ***eriss*** has investigated breeding stimuli for purple spotted gudgeon, the development of a rapid toxicity test, the use of reference waters in toxicological testing and the development of a suitable local sediment toxicity test.

Difficulty was found in procuring sac fry of the purple spotted gudgeon (*Mogurnda mogurnda*) outside of the Wet season, a factor that precluded its use in Dry season testing. ***eriss*** investigated the effect of temperature and other factors on the breeding behaviour of *Mogurnda mogurnda* (Markich & Camilleri 1997). The results determined that modification of aquaria habitat to include areas where the breeding gudgeons could seek escape from aggressive partners, use of a commercially available carnivore pellet food combined with regular feeding with live food when available, and partial water changes, could stimulate the stock to breed. These techniques are currently used with satisfactory results.

There would be considerable benefit if a rapid ecotoxicity test could be developed with adequate sensitivity. Such a test, based upon inhibition of the feeding rate of Cladocera (waterflea) as an endpoint, has been investigated collaboratively with staff and students of the University of Stirling (UK) and RMIT (Melbourne). The first project involved the development of a protocol using the local cladoceran, *M. macleayi* and local alga, *Chlorella* sp. Research determined a suitable age of Cladocera to test with, an appropriate algal cell density to allow feeding and counting of cells, and development of a rigorous method using the Coulter particle counter, to quantify cell determination. The results of the protocol (Orchard et al 2002) indicated a potential for further work. The second project investigated application of the *M. macleayi* feeding rate bioassay as a rapid screening test for complex mixtures. Results showed that application of this protocol with the species used was limited using waste waters dominated by uranium (Smith 2001). No subsequent work has been conducted.

A requirement of good laboratory practice in ecotoxicity laboratories is the need to routinely demonstrate consistency. The waters normally used in testing are pond waters from mine sites (the test water) and natural creek waters (as diluent and control). Both types of water are subject to variations in their chemical composition which render them useless for the demonstration of consistency. Rather, such demonstration requires the use of a standardised synthetic creek water and reference chemicals. The ***eriss*** ecotoxiciology laboratory carries out routine reference toxicity assessment of protocols to ensure cultures and results are comparative over time. A specific project related to variability in biological response was conducted in 1999. In this study, clonal variation of *M. macleayi* was investigated in response to uranium and cadmium (Semaan et al 2001). Results of the study showed that the current cladoceran clone has comparative sensitivity to wild clones despite at least 10 years of laboratory culturing.

In 1997 a project was initiated at ***eriss*** to develop a sediment toxicity test and to assess the sensitivity of response of the test species to uranium. A site-specific sediment test protocol was successfully developed using larvae of the midge, *Chironomus crassiforceps* (Peck

2000). No effects were observed in midge larvae exposed to sediment containing up to 5000 mg/kg uranium, the highest concentration tested. The same aquatic animals were far more sensitive when exposed to uranium present in water only (eg 72 h LC50 of 37 mg/L and LC5 (equivalent to the NOEC) of 20 mg/L, water pH of 6) (Peck 2000). Thus, uranium present in sediment presents a much lower risk to these animals than uranium present in water only.

Ecological risk assessment

The results obtained in research on the hydrological modelling of Jabiluka (section 5.2.3) have been combined with the above research on site-specific ecotoxicology and standard development to develop a quantitative risk assessment of the proposal to develop a mine and mill at Jabiluka.

Fifty thousand simulations of the water balance at Jabiluka were carrried out using the hydrological model for Jabiluka (Chiew & Wang 1999). In each simulation, the daily storage water balance was determined over a 30-year mine life, starting with an empty pond. The rainfall and evaporation record modelled in each simulation was randomly selected using an algorithm based upon the historical rainfall and evaporation records. The largest accumulated storage in each simulation 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. In this way, estimates were obtained of the storage capacity required as a function of exceedence probability.

These analyses enabled the estimation of the probability with which a given volume of water would discharge from the site to Swift Creek and the Magela floodplain arising from the following hazards (Johnston & Prendergast 1999):

- Discharge of excess water from the site in years in which the design capacity of the water management system is exceeded
- Structural failure of the water retention pond following overtopping
- Static failure of the retention pond structure, and
- Failure of the pond structure during an extreme earthquake.

Estimates of the water quality characteristics of the pond water then enabled probabilities to be derived for the occurrence of water concentrations of the principal constituents of concern (uranium, magnesium and sulphate) in downstream waters of the creek and floodplain. Quantitative estimates of ecological risk were then derived for each of the above hazards.

For example, in the case of discharge of excess water it was concluded 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. A full description of the quantitative ecological risk assessment for Jabiluka is given in Johnston & Prendergast (1999).

This risk assessment should now be repeated for the water management system that is currently in place for the standby and environmental management phase at Jabiluka. The pond at Jabiluka is smaller than that modelled in Johnston & Prendergast (1999). All water concentrations are now known for this phase of the operation and do not need to be estimated. In addition, the recent re-assessment of the toxicity of uranium should be incorporated and the statistical methods employed in the new Water Quality Guidelines can be incorporated into the risk assessment. Such a re-aassessment would be of value in providing assurances to the traditional owners and the World Heritage Committee.

5.2.5 Environmental monitoring and asssessment

Introduction

The major potential environmental impact of uranium mining in the ARR was considered to be the effects of the dispersion of contaminated mine waste waters to surface waters and since 1978 a large part of the research program at ***eriss*** has focussed on developing techniques that can monitor and assess these effects. Considerable effort has been directed at using biological indicators to detect effects on ecosystems instead of sole reliance on chemical indicators which was a common practice in the 1970s and 1980s. This work followed two themes: (1) the development of pre-release toxicity testing (Section 5.2.4) to control water release and thereby prevent adverse effects, and (2) biological and chemical monitoring to detect the occurrence of any adverse off-site effects of mining on the aquatic ecosystems.

Most of the early research by ***eriss*** focussed on the Ranger mine. The baseline research on the limnology, chemical dynamics, hydrology and erosion processes, biodiversity and ecology of the biota (phytoplankton, vascular plants, zooplankton, macroinvertebrates, fish, amphibians, aquatic/semi-aquatic reptiles, and water birds) of streams and wetlands of the ARR (Section 5.1) formed the basis for making strategic decisions about the direction of the biological monitoring research effort.

Formal development of the biological monitoring program began in 1987. The following two factors had a large influence on decisions about the direction of the monitoring program for Ranger.

- Studies of the dispersion of metals and radionuclides in surface waters indicated that most of the particulate load of Magela Creek, containing 50-70% of the radionuclide load, is deposited on the upstream end of the floodplain (Wasson 1992). Hence the area at greatest risk from water-borne contaminants was determined to lie between Ranger mine and the top section of the floodplain and, as a consequence, monitoring effort has focused on this section of Magela Creek.
- The need to select the most effective indicators given that resource constraints preclude sampling of all elements of the biota in a monitoring program. Fully aquatic organisms (or life stages) were selected because it is generally accepted that these are most at risk from release of contaminants. Benthic macroinvertebrate and fish communities, or representative taxa therein, were selected for study because they have been shown, generally, to be particularly sensitive to mining related disturbances. Macroinvertebrates are the most widely used group for biological monitoring around the world (including Australia) and the high public (including cultural) profile of fish is an important factor in their inclusion in monitoring programs.

In 1987 ***eriss*** also commenced baseline research on the upper South Alligator River, in the southern part of the ARR, in preparation for the proposed Coronation Hill gold and platinum-group mine. While research for this project effectively ceased in 1992 because of the government decision not to proceed with mining, the observational and experimental data gathered by ***eriss*** in the river and tributaries provided a test-bed for the development of monitoring designs for data on community structure that could be applied more generally (Faith et al 1991, 1995, Humphrey et al 1995).

As with the ecotoxicological research, the ultimate aim of the monitoring research was to develop procedures that could be transferred to mining companies. However, the accruing data also provided a means of assessing the adequacy of environmental protection measures in place at that time. Following a review of the program at a workshop in 1993 (Finlayson & Humphrey 1998), the design of most monitoring procedures was revised. Shortly after, the environmental protection objectives and monitoring framework were also refined to take into account nationally-accepted principles and benchmarks, including the *National Strategy for Ecologically Sustainable Development* (ESD Steering Committee 1992) and drafting of the new Australian and New Zealand water quality guidelines (ANZECC & ARMCANZ 2000) (see section 3.1.1).

In line with ESD principles, the components of the ***eriss*** monitoring program were selected to meet two important objectives of environmental protection, *early detection* of effects (precautionary management) and providing information on the *ecological importance* of any impact (maintenance of biodiversity). Early detection is provided using three approaches: water and sediment monitoring, bioaccumulation in mussels and fish, and creekside monitoring (Ranger mine only). The ecological importance of impacts is assessed from changes in biological diversity (see footnote 2, section 3.1.1) as measured using benthic macroinvertebrate and fish communities. Past research issues related to the development of these techniques are summarised below.

In 1997, following another review by an external consultant (Davis 1997), it was recommended that a set of protocols for the core monitoring procedures be compiled as a demonstration program that could be handed over to ERA. By 2000 this transfer had progressed as far as ERA taking up and implementing the rapid detection technique of creekside monitoring.

Also around this time (1998), ERA began implementing plans to mine uranium at Jabiluka. In response, ***eriss***, in part collaboration with ERA/EWLS, began collecting baseline data on water chemistry, stream macroinvertebrates and fish from streams on and adjacent to the Jabiluka lease in preparation for the need for a monitoring program should the project proceed. This research complemented the large amount of information obtained by Pancontinental Mine Ltd in this company's original preparations for the Jabiluka project, and by ERA for their 1996 EIS. The ***eriss*** baseline sampling program has continued in a revised version to the present.

In response to a tailings water leak at Ranger in the 1999-2000 Wet season, the Supervising Scientist recommended that his Division implement a routine monitoring program that would provide advice on the extent of protection of the people and ecosystems of Kakadu National Park. This was supported by the report of the ISP of IUCN in 2000. Following government approval and resourcing, this monitoring program commenced in the 2000-01 Wet season and ended the moves for transfer of the demonstration monitoring program to ERA.

The details of the present monitoring programs for Ranger and Jabiluka were presented to ARRTC in November 2001 (Humphrey & Pidgeon 2001). These details are not repeated here.

Early detection procedures

Water and sediment monitoring

Baseline water chemistry data for Magela Creek have been collected by ERA since the start of operations of Ranger mine and this continues. ***eriss*** now collects samples at the same sites as a form of check monitoring. Water chemistry monitoring of Magela Creek involves comparison of downstream data with upstream or baseline data using a control chart approach. Unfortunately, some water chemistry data prior to 2000 were analysed using techniques with poor detection limits making them of limited use for analytes where new standards are based on the distributional properties of baseline data.

Baseline data on water chemistry of the seasonal streams around the Jabiluka mine site were very limited when the Jabiluka project was re-kindled in 1996. To redress this, ***eriss*** undertook an extensive program of stream water sampling in many small streams around the Jabiluka outlier, involving weekly sampling during the Wet seasons of 1997-1998 and 1998-1999. This work has continued on a much reduced scale since then, focussing on Ngarradj Creek and its tributaries, adjacent to the proposed mine site.

Monitoring of radionuclides as concentrations of Ra226 in the surface waters of Magela Creek and Ngarradj Creek is now included in the ***eriss*** monitoring program. This analyte has been monitored by ERA in the past and the company continues this practice.

An important observation for the monitoring of water in Magela Creek came from a dye tracing study (Smith et al 1986) which tracked the dispersion of potential chemical contaminants within the creek downstream of Ranger. This showed that while there was dilution of the dye, there was a strong tendency for the plume of dye to hug the western bank of the stream. This effect was still evident at the compliance point near the end of the Ranger lease and it poses an issue about where to sample for impact detection in this anastomised stream channel. (An investigative study is currently underway to resolve this issue.)

Sediment sampling has been limited to radionuclide analysis of annual samples taken in Magela creek channel downstream of Ranger.

Bioaccumulation

Enhancement of metal and radionuclide concentrations in mussels and fish in Mudginberri Billabong downstream of Ranger could provide early warning of uptake, and hence bioavailability, of mine dispersed wastes. The data for mussels are more extensive than for fish having been collected by both ***eriss*** and ERA intermittently over 20 years (Johnston et al 1984, Martin et al 1995). However, early metal data (1980-82; Allison & Simpson 1986) may suffer from QA/QC problems associated with outsourcing of analyses. In future, bioaccumulation data will be collected at a control site as well as Mudginberri Billabong.

For Jabiluka, bioaccumulation data have been collected for fish in Ngarradj Creek and a control stream and this is continuing. ERA have also collected data from Ngarradj Creek and two other streams on the Jabiluka lease.

Creekside monitoring

Creekside monitoring is a procedure used in the sandy channels of Magela Creek to detect subtle water-column effects upon biota. Sublethal responses of organisms exposed to creek water that is pumped to test chambers in creekside shelters are measured during the Wet season. There are two creekside shelters on Magela Creek, one upstream of Ranger (control) and the other located several kilometres downstream. Two test procedures are conducted, one measuring egg production of freshwater snails and the other the survival of larval black-striped rainbowfish, each test conducted over a four-day exposure period.

Development of these tests required organisms that could be easily cultured in laboratory conditions and whose responses were sensitive to expected mine contaminants. Studies in 1991 and 1992 compared the egg production performance of several species of snail and their sensitivity to contaminated mine waste-water as a means of selecting the most appropriate species (Lewis 1992). Rainbowfish are easily bred in captivity and the survival of larvae of two species were compared in creekside experiments conducted in 1990. Black-striped rainbowfish were found to have higher survival than chequered rainbowfish in chambers with a continuous flow of creek water. While rainbowfish are at least as sensitive to uranium as other fish species tested in the ARR, their responses are not nearly as sensitive as those of invertebrate species (including those of snails); their high public profile, however, makes them a useful test species.

Initially, the program was developed in anticipation of controlled, pipeline releases of waste-water from Ranger mine, as a means of assessing the effectiveness of water-release, control measures based on pre-release toxicity testing. ERA decided not to pursue that process of water management in the late 1980s and since then waste waters have been dispersed to the creek via billabongs or, in the case of forest areas where waste waters are irrigated during the Dry season, diffusely overland. The downstream creekside shelter is sited downstream of all these sources of contamination and hence is well placed to provide early warning of adverse effects occurring during the Wet season. Creekside procedures mimic the test principles behind whole effluent toxicity testing. Over time, experimental studies have been conducted to determine dose-response relationships of the creekside test species to the major Ranger contaminants including uranium and magnesium sulfate. This information, together with parallel chemical monitoring of Magela Creek waters, will enable strong inferences to be drawn in the event of changes in responses of the test species between the creekside locations.

Assessment of ecological importance of impacts

Macroinvertbrate communities

The development of monitoring programs using macroinvertebrate communities of ARR streams has required considerable research effort on (i) the taxonomy of important invertebrate groups, and (ii) on experimental design and analysis. Thus:

(i) *Taxonomic studies*: A number of taxonomists have been contracted by ***eriss*** to describe and provide keys for important macroinvertebrate taxa (see review in Humphrey & Dostine 1994). Production of such keys was particularly important to enable species-level identifications – an essential requirement for ensuring the protection of biodiversity in areas of high conservation value.

(ii) *Experimental design and analysis*. The strongest class of monitoring and assessment designs are the so-called 'Before–After Control–Impact' family of designs (BACI), and in particular, the M-BACI design using replicated (or multiple – M) control sites but a single impact site. An important embellishment for streams is to use matched pairs of sites (upstream and downstream) in 'potentially-disturbed' and control locations (ie MBACI-P, where 'P' denotes 'Paired' differences). In this scenario it is the differences between upstream and downstream sites that are compared. Research by ***eriss*** and consultants has lead to the following refinements of the MBACIP class of design for macroinvertebrate study:

- For multivariate comparisons (ie community or assemblage data), dissimilarity measures (eg Bray-Curtis measure) may be used as the measure of paired site difference (Faith et al 1991, 1995).

- The ‘behaviour’ of dissimilarity values, and hence independence and power in these temporal replicates employed in designs, has been investigated and characterised using manipulative studies as well as observational studies in a variety of ARR stream types (permanent and seasonally-flowing) and seasons (Faith et al 1991, 1995, Humphrey et al 1995, Stowar 1997, Davidson 2000). Use was made of human-related impacts in two ARR streams (Rockhole Mine Creek and Jim Jim Creek) to test and develop experimental designs. Collectively, this research has provided a sound underpinning for the MBACIP monitoring designs now employed for the Ranger and Jabiluka mine sites. (For more detailed descriptions of these MBACIP designs, see Humphrey & Pidgeon 2001.)

Fish communities

Early studies of fish ecology in the ARR found longitudinal changes in the distribution of fish species that were related to habitat structure and seasonal migration/dispersal patterns of different species. In Magela Creek, backflow billabongs adjacent to the stream were found to be important sites for the reproduction and nutrition of many species (Bishop et al 1990). These factors together with the close proximity of the billabongs to Ranger led to a monitoring program of fish communities in 8 such billabongs along the creek (Bishop and Harland 1982). However, the removal of water buffalo from the area in the early 1980s resulted in rapid development of dense aquatic macrophyte stands in these shallow water bodies and this caused changes in the fish communities with a marked reduction in the numbers of large-bodied fish (Humphrey et al 1990). As a consequence, previous sampling methods (gillnets and seine nets) could no longer be employed. That sampling program was then discontinued in 1987 and a period of development of new sampling strategies for these areas ensued. Eventually pop-nets were decided upon as a suitable method for sampling these backflow billabongs and in 1993 a pop-net sampling program commenced (Boyden &Pidgeon 1994).

The design of the program was revised in 1994 following recommendations from a workshop (Finlayson & Humphrey 1998) to include billabongs on 2 control streams as well as billabongs on Magela Creek along a potential gradient of effects downstream of the mine. Baseline studies indicated the recessional flow period was the time of maximum fish diversity in billabongs and the sampling program was designed to sample at that time, as soon as access was available.

In seasonally-flowing streams, permanent waterbodies are obviously important Dry season refuges for fish. Downstream of Ranger in Magela Creek, these are located on the floodplain and at Mudginberri billabong at the end of the lowland sandy channel. As most mine waste contaminants would be transported to Mudginberri Billabong, monitoring techniques using fish were also developed for this site. Deep channel billabongs like Mudginberri have been relatively unaffected by the removal of buffalo and they typically contain a larger array of species than the shallow backflow billabongs. The current program uses a boat-based visual sampling procedure, originally developed for the Coronation Hill project as a crocodile-safe method for repetitive sampling of fish communities in the upper South Alligator River. Initially only Mudginberri billabong was monitored but following the 1993 workshop a similar site on a control stream was included to increase the inferential power of the program. This has proven to be very important with large fluctuations in observed densities of some ‘keystone’ fish species being shown to occur in both control and exposed sites.

Fish communities in streams on and adjacent to the Jabiluka lease are being monitored by ***eriss*** using a visual census technique, making observations from the bank. This was initially modelled on a similar procedure used to monitor effects of land application of mine waste water at Nabarlek on fish communities in adjacent streams (Pidgeon & Boyden 1994). However, the method has been modified to suit the different conditions in Jabiluka streams.

The risk of crocodile attack in these sampling programs has received close OH&S scrutiny in recent years and both programs have had to modify procedures, so far without compromising the baseline data set.

The importance of fish movement in the productivity and structuring of the fish communities led to studies if fish migration along the sandy channels of Magela Creek and its tributrary Gulungul Creek. The research on Magela creek involved measurement of numbers of fish migrating by visual counts from the bank as a possible means of detecting environmental impacts on this process during the Wet season (Bishop et al 1995). A statistical consultancy found that autocorrelation of counts during the season made this impossible (Bishop 1992). However, significant predictive relationships between hydrology (December discharge) and the total annual migration for the two most abundant migrating species were obtained (Johnston & Needham 1999). A study of the growth rate of chequered rainbowfish (the most prominent fish species in the counts) indicated that most of the migrants of this species were young-of-the-year so that the measured migration could be interpreted as an indication of recruitment for the year (Davies 1996, Ellis 1996). Nevertheless, when the monitoring program was rationalised in 1998, the study was discontinued because of the lack of a control stream with comparable visible rates of migration to provide adequate statistical inference for a monitoring program.

Further research

Apart from regular refinement of procedures for the current monitoring programs, the major future research for the monitoring group is the possible development of broader, landscape scale programs that would enable the effects of mining to be distinguished from those arising from other causes, as recommended by the ISP. Two broad groups of objectives that would assist in this are the development of (1) better knowledge of distribution and habitat parameters of endemic and/or rarer species in the landscape; and (2) better understanding of the interrelations of different elements of the ecosystems in the landscape, both through passive transport and active processes such as feeding and dispersal to anticipate and monitor for potential future impacts. A template for one such landscape-wide, monitoring approach, using fish communities of Gulungul Creek near the Ranger mine, is currently being developed (Bishop & Walden 2001).

Mining exploration is proceeding in the eastern area of the ARR in Arnhemland outside the Kakadu National Park. In order to overcome the common problem of inadequate baseline data for correctly identifying the cause of environmental change, the SSD and NLC have jointly advocated the strategic collection of regional baseline information on aquatic ecosystems in areas adjacent to mining exploration sites in the ARR. Baseline studies for biological assessment might be divided into two types:

1. surveys for conservation purposes in which rare, threatened and endemic biota are identified; and
2. gathering and identification of indicator species or groups, such as macroinvertebrates, the group most widely used for biological monitoring in Australia, for general assessment purposes.

The macro-crustacean groups, the isopods (family Amphisopodidae) and prawns and shrimps (families Atyidae and Palaemonidae) that occur in this habitat display a high degree of endemism and species diversity (Bruce 1993, Bruce & Short 1993) and are one group that could receive attention in this way. This work could be combined with similar work inside Kakadu National Park for landscape scale inventory for the ISP recommendations and serve to enhance the ecological assessment of changes detected in any broad scale monitoring programs.

5.2.6 Protection of human health

The principal hazard for humans resulting from the release of waste waters from the mines in the region is expected to be the ingestion of radionuclides in food. Hence the main thrust of research has been in the fields of radionuclide transport in surface waters and uptake into edible aquatic flora and fauna.

The concentrations of metals other than uranium are low in the ore bodies at Ranger and Nabarlek. Nevertheless, the methodology described below to determine standards for radionuclides has been adapted to set similar standards for the loads of metals discharged from the mine sites based upon consideration of effects on human health. In addition, recommendations of the National Health and Medical Research Council were taken into account in deriving the receiving water standards for concentrations of elements and compounds (Brown et al 1985).

Development of standards

In 1984 the Supervising Scientist submitted to the supervising authorities recommended standards for release of waste waters from the Ranger and Nabarlek uranium mining operations (Brown et al 1985). These recommendations included limitations on water release based upon protection of humans from radiological impact (Johnston et al 1997). The model used to relate the quantity of a radionuclide released to the intake of that nuclide by people incorporated the following three components:

- specification of the critical group and their diet,
- modelling of radionuclide transport and dispersion, and
- estimation of the accumulation of radionuclides in components of the diet of the critical group.

This model has now been extended to allow prediction of radiological impact of the Jabiluka mine, and to take into account the results of much of the research carried out in the region since 1984 (Martin 1999, 2000).

The critical group and their diet

In the case of the Ranger mine, the group most at risk would be those people who derive a significant proportion of their food from a traditional diet based on hunting and fishing in the downstream Magela system. The critical group was, therefore, identified as the group of Aboriginal people living at the Mudginberri Aboriginal camp located on Magela Creek 12 km downstream from Ranger. This camp has a population of about sixty people.

The Supervising Scientist funded a consultancy with the Australian National University (Beck 1986) to study the composition of the diet of this group, which is made up partly of traditional foods and partly of shop-brought items. However the diet proved difficult to establish with any certainty, principally because of the understandable reluctance of the Aboriginal people to accept the intrusion of privacy which is inherent in dietary intake observations which include detailed quantification.

An assumed diet for the critical group was, therefore, obtained by:

- using an average annual food intake corresponding to that observed for aborigines from the Arnhem Land region;
- deducing the estimated percentage contribution of each of the components to the total traditional diet from studies carried out by Ranger staff; and
- estimating the shop-bought contribution to the total diet from the records of the company that delivers stores to the Mudginberri community.

For the Nabarlek operation two potential critical groups were identified. One group lives near Cooper Creek downstream from Nabarlek, the other used to inhabit a site close to the Cooper Creek flood plain. The diet assumed for these groups was the same as that used for the Ranger critical group.

Bioaccumulation research

Early research by the AAEC showed that populations of the freshwater mussel, *Velesunio angasi*, in the Magela Creek system had very high flesh concentrations of Ra-226 (Davy & Conway 1974). Radiological impact via the surface water transport/bioaccumulation pathway is believed to be dominated by radium uptake by mussels (Johnston 1987), and considerable research has been undertaken on uptake mechanisms of radium and other radionuclides by this species.

Research by AAEC/ANSTO showed that the radium is stored in calcium phosphate granules in the mussel flesh. Ra-226 uptake rates by mussels were shown to be inversely proportional to both Ca and Mg water concentrations. Consequently, the high flesh Ra concentrations are an outcome of the low Ca and Mg concentrations in water of the Magela Creek and the long biological halflife of Ra in the mussel (Jeffree & Simpson 1986).

eriss studied concentrations of uranium and thorium series radionuclides in several collections of mussels from the creeks of region and used age dependencies of these concentrations to study uptake and excretion rates. From this work, a biological halflife for radium of 8.8 ± 1.0 years was derived (Johnston et al 1987). By contrast, the biological halflife for uranium has been found to be only of the order of a few days (Allison & Simpson 1989).

For other edible flora and fauna, concentration factors have been used to relate the concentrations in the water and sediment to those in food item. Deficiencies in this approach are known to exist but an assessment of the relevant factors led to the conclusion that their use was likely to be conservative provided local or site-specific values were used.

Uptake by the water lily *Nymphaea violacea* of radium and other uranium series radionuclides was the subject of studies by ANSTO (Twining 1989) and by ***eriss*** in collaboration with the University of Lund (Pettersson 1990). Radionuclide concentrations in the root and rhizome are higher than in foliage, probably due primarily to surface accumulation. Uptake of radium by the foliage has been shown to be primarily from the water rather than by translocation from the roots.

Concentration factors for edible flesh of several fauna (fish, magpie goose, filesnake, freshwater shrimp, goanna, turtle, crocodile and buffalo) have also been determined using radionuclide measurements on field-collected samples (Martin et al 1998).

Radiological risk assessment

The results obtained in research on the hydrological modelling of Jabiluka (section 5.2.3) have been combined with the above radiological research and standard development to develop a quantitative radiological risk assessment of the proposal to develop a mine and mill at Jabiluka.

As described in section 5.2.4, fifty thousand simulations of the water balance at Jabiluka were carrried out using the hydrological model for Jabiluka (Chiew & Wang 1999). In each simulation, the daily storage water balance was determined over a 30-year mine life, starting with an empty pond. The rainfall and evaporation record modelled in each simulation was randomly selected using an algorithm based upon the historical rainfall and evaporation records. The largest accumulated storage in each simulation 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. In this way, estimates were obtained of the storage capacity required as a function of exceedence probability.

These analyses enabled the estimation of the probability with which a given volume of water would discharge from the site to Swift Creek and the Magela floodplain arising from the following hazards (Johnston & Prendergast 1999):

- Discharge of excess water from the site in years in which the design capacity of the water management system is exceeded
- Structural failure of the water retention pond following overtopping
- Static failure of the retention pond structure, and
- Failure of the pond structure during an extreme earthquake.

Estimates of the water quality characteristics of the pond water then enabled probabilities to be derived for the loads of radionuclides of the uranium series disharged into downstream waters of the creek and floodplain. Using the dispersion model developed initially for Ranger and subsequently the revised model for Jabiluka (Martin 1999, 2000), quantitative estimates of radiological risk were then derived for each of the above hazards.

For example, 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. Similarly, 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. The conclusion drawn, therefore, was 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.

Issues for future research

Studies conducted to date have focussed on bioaccumulation by aquatic animal and plant species. This was due to the importance of the aquatic transport pathway, particularly during the operational phase of uranium mining operations. Despite the work which has been carried out, there remain several significant issues:

- Although considerable research effort has been expended on uptake of radium by freshwater mussels, this knowledge has not yet been incorporated into the dose assessment model for water releases.
- Knowledge of the bushfood consumption by the relevant Aboriginal groups is poor. This includes knowledge of both the range and quantities of foods eaten, as well as of food preparation methods (eg cooking methods).
- There is little available information on radionuclide uptake by terrestrial animals and plants. This pathway becomes particularly important once rehabilitation of minesites occurs.

eriss is presently undertaking projects to address these issues. This work is being carried out in such a manner as to provide Aboriginal people with more information on and involvement in the work being carried out than was the case in previous projects.

5.2.7 On-site processes to protect off-site environment

The opposition of Traditional Owners to the direct release of mine waters to Magela Creek and the decision by ERA in 1995 not to proceed with the approved release of RRZ waters led to an increased emphasis on land irrigation as the primary method of water management at Ranger and also to the investigation of other methods such as wetland filtration, enhanced evaporation and active water treatment. ERA's work on wetland filtration and active water treatment has been summarised in section 5.2.2. ERA continues to investigate enhanced evaporation but this work is not very advanced. Research on land irrigation by ***eriss*** in collaboration with CSIRO is described below.

In the early 1980s, the operators of the mines at Ranger and Nabarlek proposed the use of land irrigation (application) as a Dry season alternative to direct release of waste water to surface streams and established trials (Ranger 1985, Nabarlek 1984) to examine its adequacy. On the basis of these trials, the OSS and DME concluded that land application was an environmentally acceptable method of disposal of RP2 water at Ranger at least for a period of a few years. However, questions remained about its suitability as a long-term method of disposal, perhaps over decades. For this reason ***eriss*** undertook a collaborative research project with the CSIRO Division of Soils on land application of retention pond water at Ranger.

The project was in two phases. In the first phase, Chartres et al (1991) examined the soils and the hydrology of both the proposed Ranger irrigation area and another nearby area to obtain a preliminary assessment of their capacity to retain solutes applied during irrigation. They identified three major soil mapping units each with high gravel fractions of quartz and ferruginous material. The soils were low in clay and deficient in organic matter. They concluded that the cation exchange capacities of the soils were extremely low and that they were likely to have limited potential for the assimilation of major cations. This study did not examine the capacity of the soils to retain trace elements and radionuclides. The survey of the alternative potential irrigation site indicated four mapping units, three of which had generally similar properties to the corresponding units of the principal irrigation area. The fourth unit at Site 2 occurred along drainage depressions and was characterised by generally thicker profiles of grey, cracking clays with low gravel contents.

The second phase of this work (Willet et al 1993) examined in some detail the capacity of the soils of the Ranger land irrigation area to retain the major ions and the trace elements contained within Retention Pond 2 at Ranger. There were four main parts to the investigation:

- investigation, by batch processing methods, of the cation exchange capacity (CEC) of soils over a range of pH and ionic strength values;
- investigation, by batch processing methods, of the absorptive capacity of soils for the trace constituents Mn, U, Ra and Pb;
- simulation, by laboratory column experiments, of long-term irrigation using RP2 water; and
- simulation, in a field experiment using radioactively tagged solutes, of long-term irrigation at Ranger.

The principal conclusion of the second phase of the study were:

- A large proportion of the heavy metals and radionuclides will be retained in the soils, largely in the surface layers down to a few centimeters depth.
- The surface horizon of yellow earth soils (comprising about 60% of the land application area) has a high capacity for the adsorption of uranium, radium and lead; there should be little downward movement below the surface 4 cm layer until after 8-10 years of irrigation at normal application rates. Other soils have a lower, yet sufficient, adsorption capacity for these species, and movement below the top 50 cm of the soil is unlikely.
- Once adsorbed in the soil the radionuclides are unlikely to be remobilised easily.
- Radioactivity in plants will increase by a few per cent of the applied load of radionuclides, largely by foliar uptake.

In September 1991, ***eriss*** organised a 3-day workshop in Jabiru to review the current status of knowledge on land application as a technique for the disposal of mine waste waters, to assess the implications for regulation of the technique, and to specify future information requirements on land application. It was attended by representatives of all of the interested parties in the Region (ie the mining companies, Northern Territory authorities, the OSS, the NLC) as well as experts from other research organisations such as CSIRO, ARL (now ARPANSA) and the NTU. The proceedings of the Workshop were published (Akber 1992).

The two principal issues to be addressed in any assessment of land irrigation are (1) the potential off-site environmental impact during the operational stage and (2) the possible need for rehabilitation of the site to ensure that future land use objectives are met.

With respect to off-site environmental impact during the operational phase, the only residual uncertainty raised at the Jabiru workshop was the possible remobilisation of uranium and radium from the land irrigation site. Willet et al (1993) reported that there was some indication of remobilisation of uranium but noted that the measurement errors were large because they depended on observed differences in soil concentrations. Akber & Marten (1992) reanalysed a large number of the samples used by Willet et al (1993) using a more sensitive detector system. The retention of uranium and radium two years after the trial were measured to be 0.86 ± 0.12 and 0.84 ± 0.24 respectively. While these results are consistent with 100% retention, it was concluded that direct measurements of these radionuclides in runoff would be desirable. A limited number of runoff samples were analysed for ^{226}Ra (Martin et al 1993) and concentrations were found to be small, consistent with very low remobilisation. While the evidence indicates that loss of uranium and radium by remobilisation is small, it would be advantageous to collect further samples of runoff from the site for radionuclide analysis and to collect core samples to examine downward movement of radionuclides some 17 years after the use of land irrigation commenced at Ranger.

The primary issue to be assessed with respect to rehabilitation of the land application site is radiation exposure of members of the public when restrictions on entry to the land are removed. Three dose assessment models (by ***eriss***, DME and ARL) were presented at the workshop. When compared on the basis of a 4-hour daily occupation of the area (one model of possible long-term occupancy of the area), these models are in broad agreement and predict a dose of between 0.1 and 0.25 $mSv.yr^{-1}$ for the solute load applied up to June 1991. Relative contributions to the dose from different pathways were of the order of 10% for inhalation of ^{222}Rn, 40% for inhalation of dust, 30% for external gamma dose and 20% for ingestion. There were, however, large uncertainties in some of the pathways assessed, particularly for dust. It is desirable that a full radiological assessment (radon emanation, radionuclide concentrations in dust, gamma-ray dose rates) of the land application site at Ranger is now carried out to ensure that adequate information is available for decisions to be made on the need for rehabilitation of the land application area.

Land irrigation of untreated water contained in the Interim Water Management Pond at Jabiluka has been approved for the Dry season in 2002. This approval, for one year in the first instance, was based on the results obtained in the above research on land irrigation at Ranger. The possible long-term use of land irrigation at Jabiluka will be assessed in the current review of water management options at Jabiluka being conducted by the Jabiluka Minesite Technical Committee. While it is clear that absorption of uranium will be high in the soils at Jabiluka, it would be prudent that a detailed comparison of the soils at Jabiluka with those at Ranger be carried out and that the capacity of the Jabiluka soils for retention of uranium be assessed.

5.3 Dispersion in groundwater

5.3.1 Introduction

Changes in the surface topography at the Ranger mine site as a result of mining operations have resulted in significant changes to the characteristics of local hydrogeological systems, primarily groundwater quality and flow patterns. For example, the mined-out pits act as sinks, causing groundwater flow gradients to reverse and groundwater to flow-in to the pits. These inflows are managed with dewatering bores to minimise re-handling of water within the mine water management systems (both RP2 and process water) and to maintain pit wall stability. The presence of above-ground structures (eg tailings dam) and irrigation systems (for the treatment of mine water) result in the development of mounds which potentially leach solutes into local aquifers.

Historically, groundwater research has focussed on the impacts on local surface water and groundwater systems of seepage from irrigation systems and above-ground structures. For example, numerous modelling studies have been undertaken to quantify the likely rates and fate of seepage from the tailings dam. Considerable research has also been undertaken in the Magela Land Application Area (irrigation area) to determine solute adsorption mechanisms in soil horizons and to measure and model accessions of solutes into groundwater or surface water.

Given that decommissioning and rehabilitation will involve backfilling both pits and removal of the tailings dam, key objectives of current and future investigations are to determine options for the management of seepage to ensure that there are no detrimental impacts to downstream water quality. Similar work has also been undertaken to evaluate the potential water quality impacts associated with backfilling underground voids at Jabiluka with tailings as part of the Jabiluka Mill Alternative (Kalf & Dudgeon 1999).

5.3.2 Regional hydrogeology

The Ranger and Jabiluka project areas comprise flat lying Middle Proterozoic quartzites/sandstones of the Kombolgie Formation unconformably overlying Early Proterozoic rocks and an Archaean granitoid basement (Nanambu Complex). Surficial deposits include soils overlying Quaternary, Tertiary and Cretaceous sediments. Key stratigraphic units of hydrogeological significance include the Quaternary and Tertiary sequences, the Cretaceous Bathurst Island Formation (sandstones, conglomerates and siltstones), and the upper (semi-pelitic/psammitic schists and amphibolite), middle (pelitic/semi-pelitic schists and minor carbonate) and lower (massive carbonate-dolomite) units of the Early Proterozoic Cahill Formation.

Considerable work has been undertaken on the hydrogeology at Ranger, as summarised by Salama & Foley (1997). Baseline investigations at Jabiluka have been reviewed by Puhalovich and Foley (2000, 2002). The degree and extent of weathering is the most significant control on the occurrence and movement of groundwater in the shallower units, with groundwater levels closely reflecting seasonal rainfall patterns and groundwater flow gradients strongly influenced by topography. In the deeper units, geological structures and zones of fracturing and faulting strongly influence groundwater level responses to rainfall-recharge in overlying units. Water quality data in these deeper units suggest that groundwater level responses are essentially pressure-responses to changes in groundwater levels within overlying units. Groundwater level variations and flow patterns in upstream areas are more complex than those observed in downstream areas, suggesting greater local anisotropy and the presence of discrete permeable zones in elevated areas.

5.3.3 Groundwater management

At Ranger, groundwater management is focussed on controlling the inflows of groundwater to pits and minimising the impacts of seepage arising from the tailings dam, rock stockpiles and the disposal by land irrigation of pond waters. Pit inflows are controlled to minimise the water held within both the pond water (RP2) and process water circuits. This is achieved using two dewatering bores MB-L (at Pit #1) and DW3A (at Pit #$3). Dewatering is also undertaken to maintain relatively de-pressured groundwater levels in the area of the pits, thus ensuring pit wall stability.

Seepage from the base of the Ranger tailings dam has occurred since the time of its construction, consistent with assumptions made at the time of its design. In summary, this seepage has resulted in rising groundwater pressures below the dam and the development of a contaminated groundwater mound. Many investigations have been carried out on the geometry and behaviour of the mound, including airborne and ground-based geophysics (Lowson & Jeffrey 1988, Turner & Dillon 1988, Brown & Lowson 1990, Reid et al 1991, Richards 1992, Townley 1996, Buselli et al 1998, Buselli & Lu 1999, Buselli & Lu 2000, Buselli et al 2000, Buselli et al 2001, Lu & Puhalovich 2002). The studies have shown that leakage is controlled by fault zones which act as conduits, transmitting contaminants to downstream areas. Most leakage occurs along the fault-controlled alignment of Coonjimba Creek and is likely to be contained within existing retention pond systems. The behaviour of the groundwater mound following decommissioning and rehabilitation of the tailings dam is the subject of current investigations.

Historically, rainfall that has infiltrated the waste rock stockpiles has resulted in the development of plumes within the stockpiles. These plumes discharge as seepage to interception sumps located immediately downstream of the stockpiles and along pre-mining drainage lines from which the seepage is pumped into the pond water system. Some studies have been made on the internal hydrology of the waste rock stockpiles at Ranger, but this work is very difficult because of the complex internal structures and the deficiencies in monitoring technologies (Bennet & Plotnikoff 1995, Kuo 1996). Several investigations have been undertaken to reduce the seepage generation by reducing rainfall infiltration into the rock stockpiles. The impetus for this work has been partly the poor quality of seepage from Pit #3 rock stockpiles, but also the need to improve runoff water quality. Current research on the effectiveness of capping structures on rock stockpiles is directed towards strategies for use in the design of the final landform to limit infiltration but facilitate revegetatation and habitat reconstruction (Hollingsworth et al 2003).

Significant research was undertaken by ERA in the 1990s to assess the fate and transport of seepage from the Magela Land Application Area (MLAA) (Lowson & Reid 1994, Bowdler et al 1994, Guerin et al 1998). More recent research has focussed on the suitability of land application areas for irigation and optimising irrigation regimes to maximise evapotranspiration, minimising accessions to groundwater and eliminate waterlogging of the soil profile (Hollingsworth 1999, Hollingsworth et al 1999, Hollingsworth 2000a, Hollingsworth 2000b). Earlier investigations had been undertaken at Jabiluka in advance of the EIS (Taylor et al 1996).

5.3.4 Properties of tailings

Substantial research has been undertaken on the properties of tailings at Ranger mine. More recently, as part of the Jabiluka EIS and PER, studies have been extended in response to Ministerial environmental requirements relating to the future disposal of tailings at Jabiluka.

At Ranger, a number of earlier studies of tailings related to the prospect of ultimate storage of tailings in the tailings dam and rehabilitation of the dam in situ. These included both field and laboratory investigations of the physical, geotechnical and chemical characteristics of tailings in the dam (Emerson & Hignett 1989, Fordham & Beech 1989, Richards et al 1989, Richards & Peter 1989, Emerson & Weissmann 1990, Fordham 1990, Richards & Peter 1990, Richards et al 1990, Fordham 1991, Fordham 1992, Fordham et al 1992, Peter et al 1994, Emerson & Self 1993, Emerson et al 1993).

Later studies focussed on innovative strategies for capping the tailings in the dam as part of a potential rehabilitation strategy (Sheng et al 1997a, Sheng et al 1997b, Sheng et al 1997c, Sheng 1999) but soon afterwards, in 1997, ERA decided on the basis of a Best Practicable Technology analysis that the tailings should ultimately be return to the mined out pits and that further investigations would focus on management and rehabilitation of tailings-filled pits (Peter et al 1997, Craig 1998, Li & McGill 1999, Li & Cramb 1999, Li & Cramb 2000, Li 2000, Li et al 2001). These investigations are continuing.

A number of ancillary investigations have been carried out on barrier systems to ensure that the pit walls above RL0 are sealed against the possiblility of seepage and interaction of tailings pore fluids with groundwater, cemented paste tailings strategies (focussed particularly on future strategies for managing Jabiluka tailings as backfill for underground voids) and conceptual rehabilitation techniques for Ranger pits (Waite et al 1997, Fenton & Waite 2000, Puhalovich et al 2000, Jones et al 2001a & b, Puhalovich & Lu 2001).

5.3.5 Geochemistry and transport of contaminants

A number of groundwater modelling studies have been undertaken at Ranger since operations commenced. Initially these studies focussed predominantly on the likely long-term performance of the tailings dam and potential seepage impacts (Coffey & Hollingsworth 1976, AGC 1989, Richards 1992, Salama et al 1999). The modelling studies were undertaken in conjunction with:

- tailings characterisation;
- evaluations of the retardation characteristics of local aquifers;
- airborne and ground-based geophysical studies to detect seepage plumes and delineate aquifers and pathways, and to confirm the extent of contaminant movement; and
- surface water and groundwater studies around RP1.

The development of a whole-of-mine-site approach to groundwater modelling was initiated by Ellerbroek (1996) and later developed by Salama and his colleagues in CSIRO (Salama & Foley 1997, Salama et al 1998a). Most of the subsequent investigations have been focussed on modelling predictions of the impacts of mine operations and potential decommissioning-rehabilitation strategies on groundwater and surface water systems (Salama et al 1998b, Salama et al 1998c, Salama et al 1999, Kin & Salama 1999, Puhalovich et al 2000, Puhalovich & Levy 2000, Puhalovich & Lu 2001, Lu & Puhalovich 2002). Most models have been developed using the fully 3-dimensional, finite element, unsaturated/saturated, solute transport modelling package *FEFLOW*.

Between 1988–1993, ***eriss*** carried out a study of radium, thorium and actinium isotopes in borewaters of the Ranger minesite area (Martin & Akber 1996, 1999). This work was undertaken because ERA's monitoring showed significant increases in Ra-226 concentrations in water from some bores close to the tailings dam over the mine life. The major findings of the ***eriss*** study were:

- For the most seepage-affected bores, concentrations of Ra-223, Ra-224, Ra-228, Ac-227 and Sr increased over the period of the study.
- The increases in Ra isotope concentrations arose from competition for cation adsorption sites in the vicinity of the bore (due to increased cation concentrations, particularly Ca and Mg), rather than direct transport of Ra from the Ranger tailings.
- Formation of a barite solid phase is occurring in the groundwater and causing the removal of some Ra from solution. This results in lower Ra-226 and Ra-228 concentrations than would have been expected to arise from the cation competition effect alone.

In 1996, ***eriss*** started a similar long-term study of uranium isotopes (U-234, U-235 and U-238) in Ranger borewaters. Unfortunately, the lack of a short-lived natural U isotope makes interpretation of the results of this study more difficult than was the case for the radium isotope study discussed above, and it is expected that several more years of time-series data will be required (Martin 2000).

A detailed assesment of the dispersion of solutes from tailings repositories at Jabiluka was carried out by Kalf and Dudgeon (1999) as part of the Supervising Scientist's report to the World Heritage Committee on the Assessment of the Jabiluka Project (Johnston &

Prendergast 1999). The tailings repositories considered were the mine void and specially excavated underground silos.

The above study assessed:

- The regional hydrology in the vicinity of Jabiluka
- The properties and constituents of tailings
- Dispersion of solutes from the repositories over a period of 1000 years.

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 and the properties of the Ranger tailings were used in the calculations for Jabiluka.

A hybrid modelling approach was used 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. The models used were:

- 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.

Kalf and Dudgeon (1999) concluded that achieving a tailings permeability of less than 10^{-9} m/sec is desirable. Based upon the research carried out on Ranger tailings, they assessed that 99% of tailings in the silos at Jabiluka would have a permeability of less than 10^{-9} m/sec. Similar results were also expected for tailings in the mine void but thay concluded that care would need to be exercised in placement of tailings in the mine void to avoid segregation and extensive residual voids.

Modelling of the concentrations of solutes in the deep aquifer east of the tailings repositories in the direction of Swift Creek predicted 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 with 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 with 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 indicated 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 reached was that the wetlands of Kakadu will not be harmed as a result of the dispersal of tailings constituents in groundwater from Jabiluka.

The Kalf and Dudgeon report was assessed by the Independent Science Panel (ISP) of ICSU. The ISP, in its first report, was generally satisfied with the approach adopted but raised a number of issues. It recommended:

- isotope measurement to determine the age of groundwater
- presentation of the results of the Monte Carlo simulations in the form of cumulative probability curves
- the use of full three-dimensional groundwater models and the extension of these to include regional groundwater
- the extension of the dispersion modelling to 10,000 years.

Following the provision of further information inclusing available isotope data, cumulative probability curves and the extension of the modelling to 10,000 years, the ISP concluded in its final report that it had been demonstrated that ‘contaminant migration from the silos will be of the prder of 50 m or less in the sandstone and about 400 m or less west into the schists over a 10,000 year period with a 95% probability’. It agreed that a proposed program of dating of water from existing bore holes would not be justified but supported the suggestion that, if ERA drills a new bore in the vicinity of the ore body, dating of water collected from this bore should be carried out. The ISP also concluded that the use of the existing hybrid models was adequate at this stage and proposed that, if the site is developed, it would be worthwhile to construct a three-dimensional model as a site perrformance assessment tool.

5.4 Atmospheric dispersion

5.4.1 Introduction

The principal emissions to the atmosphere from the Ranger mine and mill are:

- dusts from the mine pit, primary crusher and calciner,
- radon from the mine pit, ore stock piles, waste rock dump and tailings dam, and
- sulfur oxides from the acid plant and power station.

Dusts from the above sources are primarily a radiological hazard for workers and members of the public because of the relatively high activity concentrations of the long-lived nuclides of the uranium series. Similarly, inhalation of radon and, in particular, the short-lived progeny of radon gives rise to radiation exposure. The dispersion of sulfur oxides gives rise, principally, to ecological risks through such processes as the formation of acid rain.

5.4.2 Exposure of workers

Since Ranger commenced operations, an Occupational Radiation Monitoring program has been in place. The purpose of the program, in simple terms, is to estimate the occupational radiation doses received by workers at the mine site so that they may be compared to dose limits (see 3.1.2). The existence and ongoing development of this program by ERA, with input by OSS and NT Government, has achieved in relation to worker exposures what has been generally achieved in relation to other potential impacts of uranium mining. That is, the impact (radiation dose to workers in this case) has been identified, methods of measuring it have been developed and its magnitude quantified, the significance of the impact has been determined through comparison with appropriate standards and measures have been instigated to ensure that impact remains acceptable. This has been undertaken within a comprehensive and mature radiological protection system based on a voluminous existing body of research. There is no need to repeat that research in the Alligator Rivers Region (ARR). However, OSS has undertaken some research in connection with its role of supervising environmental aspects of uranium mining in the ARR including radiation doses to workers and members of the public.

As mentioned in 3.1.2, the relevant exposure pathways for workers are direct gamma irradiation and the inhalation of radon progeny and radioactive dusts. The measurement of dose from external irradiation is by the use of thermoluminescent dosimeters (TLD badges) for the more exposed workers and by a combination of area monitoring and time sheets for the less exposed workers. The estimation of dose from the inhalation of radon progeny and radioactive dusts require the measurement of the concentration of radon progeny or radioactive dust in the air to which the worker is exposed, the time the worker is exposed to it and a conversion factor that relates those parameters to radiation dose. The Dose Conversion Factor (DCF) for radioactive dusts is calculated based upon the mixture of radionuclides present in the dust, the dose coefficient for those radionuclides, and the particle size distribution of the dust. The DCF is critical to the accuracy of the estimate of dose due to radioactive dust inhalation. Unlike the DCF used for dusts, the estimation of radiation dose due to the inhalation of radon progeny uses a Dose Conversion Convention (DCC) recommended by the ICRP which is derived from epidemiological data collected mainly from underground uranium miners rather than from a dosimetric model. Consequently, the particle size distribution (in particular, the fraction of radon progeny which is not attached to dust particles compared to that which is) which is vital in a dosimetric approach is irrelevant to the calculation of radiation doses from inhalation using an epidemiological approach.

Inhalation of dust is the most significant contributor to radiation dose at Ranger. Furthermore, this exposure pathway is the most sensitive to assumptions and site specific variables in relation to the calculation of a radiation dose. The work done by OSS has focussed on site specific parameters for the calculation of radiation dose from the inhalation of radioactive dusts. During the 1980s OSS calculated Derived Air Concentrations and Annual Limits of Intake for radioactive dusts with AMADs of 1, 5 and 10 microns (Carter 1983; Woods 1985). OSS also measured the AMAD of product dust at two Australian uranium mills (Woods 1986).

Following the publication by the ICRP of updated dose coefficients, OSS calculated dose conversion factors for ore, product and tailings dust (Zapantis 1998). These calculations considered the presence of Thorium and Actinium series isotopes, which had been ignored previously and assumed an AMAD of 5 microns. These dose conversion coefficients are thus based upon assumptions which more closely approximate reality than those previously applied. They were adopted by ERA and are now stipulated in the Authorisation issued by the NT Government for Ranger and Jabiluka as applicable.

All of the calculations above assumed the total loss of radon from dust particles. The actual loss of Rn from dust particles was measured and a relationship between radon loss and the dose conversion factor for ore dust was derived in 1999 by OSS and published in 2001 (Zapantis 2001). This work indicated that the DCF currently in use at Ranger could be high by a factor of approximately 1.5. There are other factors which lead to a significant overestimation of radiation doses such as ignoring the protection afforded by airstream helmets when calculating radiation doses. Assuming that the epidemiological and dosimetric models produced by the ICRP are not fundamentally flawed, the conclusion is that radiation doses estimated for workers at Ranger exceed, probably by a factor of two for some workers, the actual doses received due to the conservatism built into the calculations. There is no great need for additional research on worker doses at Ranger if one accepts the common practice (in radiation protection) of conservatism. However, further work could be done in three areas; the first being a more robust examination of radon loss from dust particles, the second being the development of a system which measures the concentration of radioactive dust in the breathing zone of a worker whilst wearing respiratory protection, and the third being the measurement of the AMAD of ore and product dusts in a range of exposure scenarios.

The estimation of radiation doses currently received by workers at Jabiluka is subject to essentially the same factors as those discussed above in regard to Ranger and so doses would tend to be overestimated. However, as the most significant exposure pathway for workers at Jabiluka is gamma irradiation, the extent to which radiation dose is overestimated is less than at Ranger.

The more significant issue is predicting what radiation doses might be if mining at Jabiluka proceeds. A significant volume of work was commissioned by ERA on radiological protection of workers as part of the Jabiluka Environmental Impact Statement and Public Environment Report. This looked at all aspects of occupational radiological exposure at the proposed Jabiluka underground uranium mine. OSS contracted a recognised international expert in the field of uranium mine ventilation, Dr Howes from the UK, to review this work. Dr Howes's conclusion was that the occupational dose limit could be achieved, however the relative contributions of different exposure pathways were different to those predicted in the EIS. Considering the comments of Dr Howes, and other relevant information, OSS concluded that the actual doses received would probably be less than those predicted in the EIS due to the conservatism built into key parameters used in the EIS as the basis of the dose prediction.

The development of the ore drive and footwall drive at Jabiluka, which was completed on 4 July 1999, allowed ERA, through its consultant, to undertake investigations to determine by direct measurement parameters which significantly influence the radiation doses which workers could potentially receive. Those investigations confirmed that key parameters had been significantly overestimated in the EIS. This is offset by a higher average ore grade than was assumed in the EIS. Overall, the available data indicate that the gamma dose will not exceed that predicted in the EIS and the dose from the inhalation of radon progeny and radioactive dust will be significantly below that predicted in the EIS. Once mining commences at Jabiluka, there will be a need to fully characterise the radiation environment to ensure that parameters used in the calculation of doses, particularly from the inhalation of dusts and radon progeny are appropriate.

5.4.3 Dispersion of long-lived radionuclides in dust

Initial estimates of the airborne concentrations of uranium in dusts at Jabiru East (about 3 km from Ranger, Figure 2) were made by ANSTO and presented to the Ranger Uranium Environmental Inquiry. These estimates were based on a gaussian plume dispersion model and an assumed source inventory. Concentrations of other nuclides were not calculated specifically but the ANSTO data were subsequently used to derive an estimate of the radiation exposure of the public living in Jabiru East arising from the presence of all the long-lived nuclides in dust. The estimated dose was about 0.1 mSv per annum, one-tenth of the current limit on exposure for members of the public.

Since the start of mining, ERA has carried out an extensive monitoring program for radionuclides in the environment, including long-lived nuclides in dust. Such measurements include the contributions of the mine-related component and the natural background. ERA attempted to distinguish between these components by correlating observations with wind direction but this was done on a seasonal basis only using data on the prevailing wind direction. The estimated annual dose for a member of the public living in Jabiru East was about 0.25 mSv, a quarter of the annual dose limit (Koperski 1986).

Because of the apparent significance of this pathway a collaborative research project was begun by ***eriss***, the University of Lund and ERA to discriminate between background concentrations and those that are attributable to the mining operation. The objective was to measure radionuclide concentrations in airborne and dry deposited dust as a function of distance from the mine site and hence to separate the mining-induced component from background. The principal conclusions of this project were (Pettersson et al 1987, Pettersson 1990, Pettersson & Koperski 1991):

- The concentrations of the long-lived nuclides of the uranium series in air-borne dust decrease by more than two orders of magnitude between the mine pit and Jabiru East.
- The data for the uranium series nuclides are consistent with an inverse cubic dependence of concentration versus distance from the mine pit.
- At Jabiru East the concentrations of uranium series radionuclides are higher than those of the thorium series by more than one order of magnitude.
- The estimated radiation exposure of members of the public due to radionuclide transport on airborne dusts is about 0.01 mSv in a year.

eriss has also carried out a study of uranium and thorium series radionuclide concentrations in rainwater at Jabiru Town and Jabiru East (Martin 1996, 2000). Findings arising from this work included:

- A substantial fraction of the measured activity concentrations of ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra and ^{210}Po in rain were due to below-cloud washout of dust transported from the Ranger mine.
- Concentrations of these dust-related radionuclides decreased to one half or less of their initial value after the first one to two millimetres of rainfall.
- The mine-related dose estimate for drinking of rainwater collected at Jabiru Town during the Wet season is about 0.008 mSv in a year.

5.4.4 Dispersion of radon and radon progeny

Since the exposure due to naturally occurring radon progeny in the region is about 1-2 mSv per annum, one of the challenges of determining the mine-related dose due to radon progeny has been distinguishing between the mine-derived and natural background signals.

In 1986 ERA made an estimate of radon progeny exposure of members of the public that was based upon the results of the radiation monitoring program and made the same assumptions about the prevailing wind direction as those described above for dusts. The resulting estimated dose from the mining operation was 0.03 mSv per annum (Koperski 1986).

Subsequently, ***eriss*** developed, in collaboration with ANSTO, a method for distinguishing between naturally occurring and mining-induced radon and radon progeny concentrations based on simultaneous measurement of radioactivity concentrations and wind speed and direction. The method was applied for a period of three years to enable estimates to be made of mining-induced radiation exposure of members of the public at Jabiru East and Jabiru Town. Some of the findings of this work were (Akber et al 1992a, b):

- The Ranger mine area is the largest localised source of radon within the area.
- The principal source of radon at the minesite is the ore stock pile but the tailings dam and mill plant may also be responsible for a significant fraction of observed concentrations.
- The diurnal variation in radon and radon progeny concentrations is large, with high concentrations occurring under inversion conditions in the early morning.
- Atmospheric concentrations of radon and radon progeny in the Dry season are higher than those in the Wet season by about a factor of two.
- The measured mine-derived effective doses were 0.05 $mSv.y^{-1}$ for juveniles and 0.04 $mSv.y^{-1}$ for adults living in Jabiru and 0.21 $mSv.y^{-1}$ for juveniles and 0.16 $mSv.y^{-1}$ for adults living at Gulungul Creek camp near Jabiru East (in 1989–90).

A simplified version of the method, but one adequate for routine monitoring, is now used routinely by ERA as part of its monitoring program.

Dispersion modelling

eriss has been involved in development of two models for atmospheric dispersion of radon and radon progeny. The first is a gaussian plume model developed with ANSTO, primarily for prediction of radon dispersion (Akber et al 1993). As a part of this work, meteorological data were collected over a yearly cycle using an instrumented 27 m tower installed at the ***eriss*** Jabiru East laboratory site. In addition, qualitative field observations of two simulated radon plumes were made, one using burning tyres for long range (10 km) observations and the other using marine flares for short range (200 m) observations.

The second model was developed with Queensland University of Technology and used a modified grid-cell approach to model radon progeny ingrowth and deposition (Martin, 2000). This work was carried out because experimental data showed that the radon progeny unattached fraction at Jabiru and Jabiru East is unusually high (annual average 0.14 for Jabiru East; Akber & Pfitzner 1994). The modelling results showed that the Ranger mine-derived fraction of the radon progeny concentrations at Jabiru Town are likely to have similar unattached fractions to the total (ie mine plus natural) unattached fractions observed experimentally. Predicted progeny PAEC at Jabiru Town from the Ranger operation was 2.6 nJ m^{-3} (equilibrium factor 0.16), comparing well with the experimental value of 3.1 nJ m^{-3} (at 15 m height) reported by Akber et al (1993).

For prediction of radon progeny concentrations in air resulting from the Jabiluka operation, ERA used the COMPRAD gaussian plume model (Supplement to Draft EIS, section 10.2.1). This gave a predicted mine-derived PAEC of about 0.5 mWL (10 nJ m^{-3}) at Mudginberri, with a consequent dose estimate of 0.1 mSv in a year (Draft EIS, section 9.10.3). Subsequently, ERA reported on a run of a USEPA-Gaussian model incorporating a digital terrain model (appendix L.8.6 to JMA PER) which yielded a dose estimate for Mudginberri of 0.5 μSv in a year. Modelling of atmospheric dispersion in a complex terrain (such as that around Jabiluka) is difficult, and it is likely that only collection and analysis of experimental data will resolve the disagreement between the model results.

5.4.5 Dispersion of sulfur oxides

In the second report of the RUEI (Fox et al 1977), concerns were expressed about the possible effects on vegetation and the acidity of rainwater arising from the dispersion of sulfur oxides from the sulfuric acid plant at Ranger. It was recommended that ERA be required to reduce sulfur dioxide emissions from the acid plant by installing of a stack gas scrubber. ***eriss*** has investigated the significance of the dispersion of sulfur oxides (arising not only from the acid plant but also from the power station at Ranger) by:

- modelling the dispersion of sulfur oxides (Noller et al 1990);
- measurement of dry deposition rates of sulfate at Jabiru East (Noller et al in ARRRI 1985, p62);
- measurement of gaseous and particulate sulfur oxides in the ambient air at Jabiru East; and
- measurement of sulfate deposition in rainwater throughout the Region (Noller et al 1990).

The maximum probable deposition rate of sulfur oxides at Jabiru East deduced from modelling was about 10 eq-S/ha (Gillett et al 1990). The dry deposition of sulfate was measured on a number of occasions during the 1983 Dry season at Jabiru East and at two other stations in the vicinity; the mean result was about 0.02 eq-S/ha, a value substantially below that estimated from the dispersion model, suggesting that some of the assumptions inherent in the model used were invalid.

The significance of the measured deposition rate of sulfur oxides can be assessed by comparing it with the input to the soil and plant system from rainfall. Measurements of sulfate in rainfall of the Region have shown that such sulfate is naturally occurring and prevalent throughout the Region. This natural input load of sulfate to the soil and vegetation system is in the range 20-40 eq-S/ha; by comparison, the input due to dispersion from the Ranger operation is trivial.

The measurement of sulfur oxide concentrations in ambient air of the Region is difficult because such concentrations are very low and conventional techniques are not sufficiently sensitive. Sample collection of gaseous and particulate sulfur oxides has, however, been carried out using a diffusion denuder technique; this was used to integrate ambient loads over a period of about two days. The mean concentration of sulfur dioxide in the atmosphere at Jabiru East was measured to be about 0.8 $\mu g/m^3$, a value that is in good agreement with estimates presented at the RUEI and which is lower than the limit recommended by the US Environmental Protection Authority by a factor of one hundred.

The conclusion of this work is that dispersion of sulfur oxides from Ranger does not constitute a significant hazard.

5.4.6 Issues for future work

The majority of radon and radon progeny measurements in the ARR have been carried out at only a few locations, these being at or within a few kilometres of the Ranger and Nabarlek minesites during their operational phases (ERA also reported average monthly data at the Jabiluka site in their Draft EIS, section 9.9.5). In 1996 ***eriss*** began the establishment of a regional radon and meteorological network. The network is providing long-term information on radon concentrations in air (a) at and near former uranium minesites (ie Nabarlek post-rehabilitation, South Alligator Valley mines), (b) at strategic locations within a few kilometres of the Jabiluka minesite, (c) at 'background' sites far from uranium mining activities, and (d) at strategic locations around the Ranger site (primarily for testing of atmospheric dispersion models). Four stations are currently operational. One of the network stations will be kept permanently at Mudginberri as a part of the monitoring regime for the Ranger and Jabiluka operations.

One of the greatest uncertainties for radon and radon progeny modelling remains the source term ie the exhalation rate of radon from mine material surfaces. This is particularly important when considering rehabilitation options such as the depth of cover over tailings and low grade ore residues. ***eriss*** has begun work on this problem with measurements of geographic variability of radon exhalation over the rehabilitated Nabarlek site. More detailed work for the Ranger/Jabiluka region, including the important influence of soil moisture, will begin in 2002 with a collaborative project with Queensland University of Technology.

5.5 Rehabilitation

5.5.1 Introduction

The primary goal for the rehabilitiation of the Ranger mine site is that the operating company must rehabilitate the Ranger Project Area 'to establish an environment similar to the adjacent areas of Kakadu National Park such that, in the opinion of the Minister with the advice of the Supervising Scientist, the rehabilitated area could be incorporated into the Kakadu National Park.' A major objective is 'erosion charcteristics which, as far as can reasonably be achieved, do not vary significantly from those of comparable landforms in surrounding undisturbed areas.'

The principal objective of research carried out on rehabilitation by ERA and ***eriss*** has been, with respect to Ranger, to determine the design characteristics of the rehabilitated landform at the minesite that will ensure that the above goal and objective will be achieved. Although Nabarlek is not within the Park and the procedure for determining rehabilitation objectives was different, in practical terms the objectives for rehabilitation at Nabarlek were similar to those at Ranger and the research needs were very similar.

A threshold issue for rehabilitation at Ranger for a number of years was the question of whether or not ERA would be required to transfer all tailings contained in the above grade tailings dam to the mined out pits at the end of mining. The original Environmental Requirements allowed for the possibility that the tailings dam could be rehabilitated *in situ* but required that the Supervising Scientist be satisfied that, should this be done, 'the environment be no less well protected than by depositing or transferring the tailings to the mine pits'. ERA made its position clear throughout the 1980s and the early 1990s that its preferred option was rehabilitation of the tailings dam *in situ* and much of the rehabilitation research conducted by ***eriss*** and by ERA was directed at gaining the information upon which the assessment of such a proposal could be based. In the late 1990s, however, ERA changed its position and committed the company to final disposal of all tailings in the mined out pits at Ranger. This is now a requirement on the company under the revised Environmental Requirements.

To address the above issues, the rehabilitation research programs of ERA and ***eriss*** have, over the past twenty years, examined the following:

- Geomorphic stability of the Ranger mine site and the Magela Creek
- Characteristics of the rock materials and the incipient soils forming from them
- Geotechnical properties of the materials forming the landforms
- Internal structure of the landforms
- Hydrology and seepage characteristics
- Development of landscape evolution models
- Surface form and erosional behaviour
- Dispersion of erosion products in the immediate vicinity of the Ranger mine site, ie in the tributaries of Magela Creek that drain the mine site
- Dispersion of erosion products in the Magela Creek and the Magela backwater plain.

As discussed in section 3.3, revegetation aspects of rehabilitation are discussed separately in section 5.6.

5.5.2 Geomorphic stability of the Ranger mine site and the Magela Creek

The selection of geomorphologically stable sites for the containment of radioactive mine tailings and sub-economic ore is necessary to prevent a range of long-term natural hazards from exposing and transporting such materials off site. Mine tailings contain residual long lived isotopes with very long half lives. Hazards such as channel incision, lateral migration, channel avulsions, flood stripping, flood inundation, surface and subsurface erosion, mass movements, gully initiation, headward growth of tributaries and sedimentation all need to be assessed when selecting a containment site and method.

Nanson et al (1990) and East et al (1993) assessed the future long term stability of the Ranger Uranium Mine area by examining the Quaternary (approximately the last 2 million years) landform evolution in the vicinity of the mine. This work was based largely on the Quaternary history of the sand-bed anastomosing (multiple) channels of Magela Creek and its tributaries near the mine (Nanson et al 1990; 1993; Roberts 1991). Extensive radiocarbon, thermoluminescence and uranium/thorium dates were used to establish the geochronology. The premise of their work was that future landscape changes can be confidently predicted from geomorphological events during the Holocene Epoch (ie the last 10000 years). In essence, they concluded that the oldest landforms were the most stable and hence the safest for siting containment structures.

Magela Creek flows next to the mine along the western side of its valley and is flanked on the east by extensive Pleistocene (10 000 to 2 million years ago) alluvium (Nanson et al 1990, 1993). The ancestral Magela Creek during lower sea levels eroded its bed producing a deep trench cut into Pleistocene alluvium and bedrock (Nanson et al 1990, 1993). This trench was progressively backfilled during the Holocene following sea level rise to about its present position at 6.5–5.8 ka (Woodroffe et al 1987). The medium to coarse sand channel-fill is 8–12 m deep, 200–400 m wide and prograded progressively downstream from the North Arm junction to Mudginberri Billabong (Nanson et al 1993). Downstream advancing sand deposition was followed by an accelerating rate of vertical deposition (Roberts 1991). Sand is now being deposited above the level of tributaries, resulting in their damming and formation of backflow billabongs and deferred tributary junctions. The alluvial trench upstream of Mudginberri has been essentially infilled with sand and further deposition will bury much older marginal alluvium (Nanson et al 1993) on the right bank side of the valley where there are currently extensive stands of *Melaleuca viridflora*. At about 6 ka, Magela Creek discharged into a relatively narrow tidal estuary about 6–7 km upstream of Mudginberri which had been converted to freshwater by sand deposition at about 4 ka (Clark et al 1992a).

Nanson et al (1990, 1993) found that the mine site tributaries did not erode deeply into their bedrock basement during lower sea levels and joined Magela Creek at waterfalls. Pleistocene sediments are preserved at depth in both Georgetown and Gulungul Creeks. On Georgetown Creek, there is a complex sequence of stratified sands, mottled clays, sandy clays and basal gravels, filling a shallow bedrock valley. Age reversals were found and indicate that thermoluminescence may not be an appropriate dating technique in small catchments (Nanson et al 1993). On Gulungul Creek, thin gravel and extensive medium to coarse sand filled the bedrock trench to about 79 ka. Then a laterally migrating channel was active between 23 and 12 ka depositing a sheet of fining upwards clean sand. Probable Holocene sediments form a thin cap on top of the late Pleistocene sand.

Nanson et al (1990) and East et al (1993) defined and mapped five classes of geomorphological stability near the Ranger mine based on the intensity of past erosional and/or depositional processes. The least stable sites (category 1) were readily identified as the currently active landforms, namely the Magela Creek channel, backflow billabongs and levee swales. Clearly these are unsuitable sites for containment structures and have been completely avoided by ERA. The most stable site (category 5) was the oldest landform, the extensive undulating lowlands which Hays (1967) called the ‘Koolpinyah Surface’. Although this surface was originally believed to be a Tertiary (65 to 2 million years ago) lateritised palaeoplain (Hays 1967, Williams 1969, 1991, East et al 1993), thorium-uranium disequilibrium dating of iron pisoliths from the same shallow soil horizon below the Koolpinyah Surface yielded ages of only 135 to 202 ka, with a mean of 176 ka (Short et al 1989). Short et al (1989) interpreted this result to mean that there was a second phase of lateritisation of the Koolpinyah Surface in the late Quaternary following the earlier main Tertiary phase. More recent work by Nanson et al (1993) found thorium-uranium dates of >400 ka on iron pisoliths in a river terrace on Magela Creek inset into the Koolpinyah

Surface. Isotope ratios in one sample showed that the pisolith was probably older than 1.3 Ma. Therefore, the Koolpinyah Surface must be older than the river terrace. Nanson et al (1990) and East et al (1993) recommended that long term containment structures associated with the Ranger mine should be sited on this surface. The tailings dam as well as pits 1 and 3 are obviously located on the Koolpinyah Surface which has formed on weathered Cahill Formation which hosts the uranium.

The largest storm since the commencement of mining at Ranger was recorded on 4 February 1980 when 303 mm fell between 0200 and 1800 h at the pluviometer at the Jabiru anenometer tower (Water Division 1982). Recent work by the Bureau of Meteorology (1999) found that the 24 hour probable maximum precipitation estimated by the Generalised Tropical Storm Method for a 1 km^2 area at Jabiluka was 1380 mm. Jones et al (1999) cautioned that this estimate may have been underestimated by up to 35%. Clearly, the Ranger mine site has only experienced relatively small rainfall events in comparison to the probable maximum precipitation since mining began. It is essential that the probability and magnitude of extreme storms and floods are more accurately defined because of their potential significance for soil erosion, sediment transport, channel changes and avulsions. Erskine and Saynor (2000) recommended that detailed analyses of the slackwater deposits and palaeofloods in the sandstone gorges on the East Alligator River and Magela Creek should be undertaken to determine whether any catastrophic floods have occurred in the Alligator Rivers Region during the mid- to late-Holocene. However, alternatively, the probable maximum flood could be estimated by standard techniques for Magela Creek opposite Ranger mine. Whatever approach to the estimation of extreme events is adopted, the risk of avulsions and/or substantial channel erosion into pit 3 by a probable maximum flood needs to be evaluated.

Erskine and Saynor (2000) identified at least two avulsions preserved on the East Alligator River floodplain near Cahills Crossing and East et al (1993) highlighted the potential for channel avulsions on the Magela Creek sand zone next to the Ranger mine. Catastrophic floods are known to cause large scale channel erosion and massive bed sedimentation (see review in Erskine and Saynor 2000). No assessment of the potential for, and causes of, channel avulsions in the Alligator Rivers Region and their significance for erosion of the Koolpinyah Surface next to Magela Creek at pit 3 at the Ranger mine has been conducted. The integrity of a rehabilitated pit 3 during a probable maximum flood should be evaluated because it is located near the outside of a bend on Magela Creek which is known to be actively aggrading (Nanson et al 1993) and currently spilling out of the alluvial trench in which it has been confined throughout the Holocene. Substantial bed aggradation during a probable maximum flood would increase the risk of erosion next to pit 3.

5.5.3 Characteristics of the rock materials and the incipient soils formation

Early CSIRO investigations were initiated to compare incipient soils forming on waste rock ('minesoils') with natural undisturbed soils in the surrounding area. The objective was to define the basis for an effective revegetation strategy, given the paucity of natural topsoil available for spreading over the landform for revegetation purposes (Milnes & Armstrong 1986, Milnes 1988, Fitzpatrick & Milnes 1988, Milnes 1989 Milnes 1991). This work was undertaken essentially on the northern waste rock stockpiles.

The essential findings were that weathering of much of the rock materials exposed on the surface of the stockpiles was rapid. Comparisons were made with the end products of weathering in the soils ans saprolite of the natural landscape. A surface stony armour developed quickly, together with an underlying vesicular silty crust, similar to desert pavement (Bourman & Milnes 1985). This effectively sealed the surfaces and was responsible for very low infiltration rates. The common development of white efflorescent crusts of epsomite ($MgSO_4.7H_2O$) was noted. These indicate a ready source of Mg and SO_4 which is probably a combination of RP2 water (used in dust suppression), rock weathering (from chlorite and sulfide minerals) and leaching by Wet season acid rainfall (Noller et al 1990), Water repellent fine sediment was also observed accumulating in hollows on the surfaces of the stockpiles. Below the compacted surface layer, the stockpiles had a very low bulk density and consequently appreciable deformation and settlement was anticipated in the long term.

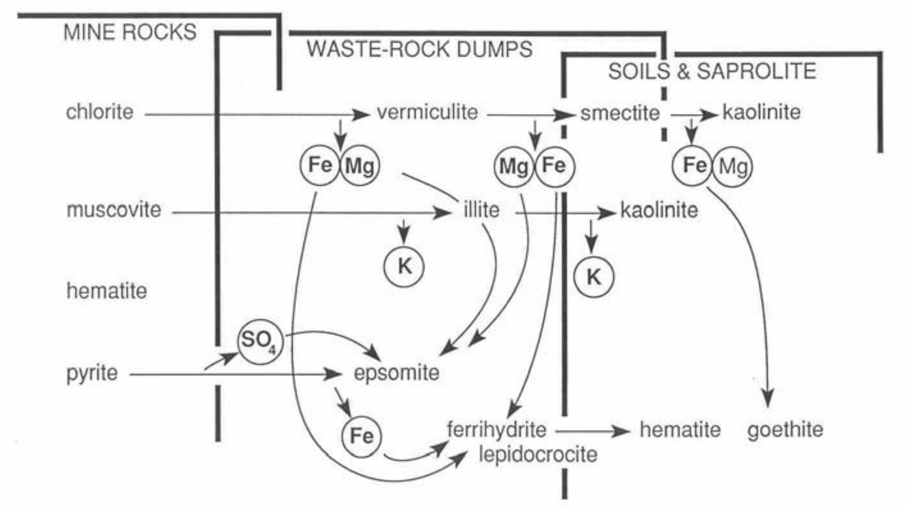

Fig. 3. Simplified schematics of rock weathering and weathering products in terms of major minerals and major element rearrangements.

Figure 4 Simplified schematics of rock weathering and weathering products in terms of major minerals and major element rearrangements (from Milnes 1988)

Milnes and Fazey (1988) looked briefly at the issue of acid leaching of waste rock and stockpiled ore at Ranger and reported chemical analyses (including total S and U) for a number of samples. This was initiated as a result of observations by Fitzpatrick (1986) of pseudo-acid sulfate soils on and around the margins of the waste rock landform, and because high levels of U were recorded early in 1987 in retention ponds 2 and 4 immediately following the construction of a stockpile of high grade ore ('7P') in the catchments of these water retention ponds. Water ponding beneath the stockpile as a result of depression of the natural landsurface (Richards 1987) had a pH of 5.1 and a U concentration of 150ppm. The analytical data indicated that total S levels in the samples of waste rock and ore were, with few exceptions, less that 0.04%, corresponding to very low concentrations of sulfide minerals. However, one rock sample from the '7P' ore stockpile contained 3.51% S and exhibited conspicuous acid leaching and weathering features.

A number of distinct 'minesoil' types were recognised on the waste rock stockpiles (Fitzpatrick 1986). Fitzpatrick noted that K and S released during weathering of waste rock were 'sufficient' for plant growth in minesoils, and 'sufficient' P was available to support deep-rooted vegetation. However, the very high ratios of Mg to Ca in the minesoil solution could affect the nutrition of some plants. The uptake of contaminants by *Acacia holosericia* established on the stockpiles was investigated but no significant uptake of U compared to controls was detected. However, there were differences in terms of the concentration of Zn, Fe, Mn, K, S and P with Fe, K, S and P being enriched in plants growing on the stockpiles relative to controls.

Minesoil development is rapid. Within two years of construction of waste rock stockpiles, properties such as colour mottling due to increased hydromorphy, variations in soil texture as a result of water erosion of fine material, structure development, decrease in pH due to pyrite oxidation and sulfate weathering were recognised by Fitzpatrick et al (1989). All minesoil samples contained high exchangeable Mg levels. High concentrations of exchangeable K and S were measured in pseudo-acid sulfate soils. Minesoils were described as more fertile than the natural undisturbed soils of the area, and stockpiled natural soils, in terms of plant seedling growth. However, both P and N were deficient for optimal plant growth. In addition, glasshouse bioassays of minesoils indicated that symbiotic micro-organisms (rhizobia and mycorrhizal fungi) were absent or poorly represented in minesoils, other than those with a vegetation assemblage. Concentrations of U in plant tissues were lower than those in minesoils, indicating that there was no preferential (active) uptake or accumulation of U by plants.

In summary, minesoils are rocky and have no serious limitations to plant growth. In time they will develop into soils that are similar to those in the natural landscape.

5.5.4 Geotechnical properties of the materials and the landform

The waste rock stockpiles are constructed by dumping successive truck loads of material to form layers or terraces which are flattened by bulldozer and extended by edge-tipping. Each layer or terrace is approximately ~11m high and has a compacted surface caused by heavy equipment traffic (bulldozers, dump trucks). The batters at the edges of the stockpile terraces are at angle of repose (generally less than 40^{o}, and usually about 36^{o}, or 1 in 1.4). Initial compaction of the surfaces of the stockpile terraces is generated by vehicular traffic. Surfaces are continually watered during construction to reduce dust levels and so initial compaction takes place at high moisture levels. Further compaction of the landforms occurs as the height of the stockpiles increases and is due to increasing overburden stresses and shearing, which take place as the dump settles or consolidates.

The mass stability of the landforms is a function of material properties, water content and internal structure. Low density materials and high water contents within the landform may cause instability. In particular, water could enter structures such as tension cracks and pipes at the tops of slopes and wet potential failure zones. Changes in near-surface groundwater levels from dry to Wet season could influence hydraulic gradients and generate seepage from the toes of slopes, thus generating lower stability and failure.

Early investigations of the geotechnical properties and behaviour of the waste rock landforms were carried out by Richards et al (1986) and were focussed on assessments of slope stability. Bulk density was measured and indicated a significant variation between the surface crust of the dump (up to 2300 kg/m^3) and the underlying materials (densities as low as 900 kg/m^3). Shear strength of waste dump materials was also assessed, although the high variation in density throughout the dump made it difficult to determine a representative value from discrete samples. The work suggests that in the absence of groundwater within the dump, the dump is currently stable for slopes of 36 degrees or less, irrespective of height. Three possible mechanisms for reduction in this material strength were identified:

- development of water tables in the dump and seepage from the slopes;
- long-term creep along possible failure surfaces reducing the shear strength (mainly cohesion);

- further weathering and degradation of the materials in the dump also reducing shear strength.

Richards (1987) demonstrated that there was a possible substantial depression of the original landsurface beneath ore and waste rock stockpiles at Ranger Mine and that this might result in significant ponding of water in the base of the waste rock landforms for long periods of time. Based on the observation that ponded water beneath the high grade ('7P') ore stockpile had a pH of 5.1 and contained 150ppm U, Richards pointed out that this phenomenon could facilitate leaching of contaminants from ore and waste rock (with consequent seepage to groundwater or surface water) and accelerate weathering. Richards proposed that drainage systems should be constructed prior to construction of the stockpiles to prevent ponding of waters in the depressed zones.

Henderson (1992) investigated the long-term structural stability of the slopes on the waste rock stockpiles at Ranger, particularly against mass sliding. She developed a procedure utilising photography and computer-based image analysis to measure particle size distributions for waste rock materials after various periods of exposure on slopes of up to 7 years. Mineralogical data were obtained for corresponding subsamples from the batter slopes, and for supplementary samples of waste rock materials representing more advanced stages of weathering. In addition, laboratory compaction and triaxial compression tests were carried out on these materials. The conclusions from the investigations were that:

- angle of repose batter slopes for 30 m high stockpiles are stable under conditions pertaining in the landform for the life of the mining operation. Stockpiles up to 40 m high could also be stable but further investigations were recommended to test this design limit;
- batter slopes are stable for at least 5–10 years after stockpiling. The crucial stage of weathering occurs after 5–10 years when shear strength under low normal stress is at a minimum;
- the critical mode of failure is likely to be sliding along a 'softened' base because of the depression in the natural landsurface created by the weight of the landform; and
- with regard to rehabilitated landforms, slopes of 1:3 would be stable against mass sliding in the long term.

5.5.5 Internal structure of the landform

The internal structure of the waste rock and below economic grade ore landforms has been generated as a series of digital elevation models and orthoimages from a variety of data sources, including annual aerial photographs (from 1980), paper maps and digital map files (Soole 1998). Apart from illustrating the development of landforms over time, the locations of specific features such as compacted stockpile surfaces, haul roads, drainage-ways and water retention ponds are shown. These features, which are effectively structural inhomogeneities, are likely to be important in the long-term evolution of the landforms, particularly in terms of hydrology and possibly mass stability. However, there is sparse information about the location of particular rock types or materials with particular properties.

5.5.6 Hydrology and seepage characteristics

Following the observation by Richards (1987) that the waste rock stockpiles were likely to be significantly depressing the underlying landsurface and causing ponding of water, Milnes and Fazey (1988) briefly assessed the potential for acid weathering and leaching of U from ore stockpiles. It became clear that, given appropriate conditions, weathering processes (including acid generation from sulfide degradation) might be very important in mobilising U and other contaminants from both ore and waste rock stockpiles (and hence the final landform) at Ranger Mine. As a result, further investigations of the interior of the waste rock stockpiles were foreshadowed at this time.

One approach was to sample and evaluate the characteristics and fate of contaminants in runoff and seepage from the waste rock landform (Beech et al 1990, Nisbet 1990) and in this way make an assessment of the weathering and leaching reactions taking place on and within the landform. Analyses of waters, sediments and plants in drainage channels and water retention ponds adjacent to the various stockpiles were undertaken in this context.

In the case of water samples (February 1990), the major ions were Mg and S. The highest concentrations of Ca, Mg, and S were measured in the waste rock and very low grade ore stockpile drains. The highest concentrations of U and Mn were determined in the very low grade ore stockpile drain.

A second approach was to drill through the waste rock and low grade ore stockpiles with the objective of sampling the materials to determine the nature of weathering processes and products and to assess the internal hydrology of the landform (McAllister & Unger 1994). Only a small number (five) of holes were successfully drilled and cased (Figure 5) and three bores provided useful information over the monitoring period: the others remained dry. Water levels were gauged on a fortnightly basis from December 1992 and chemical analyses of water samples taken at monthly intervals were undertaken from October 1993. Irrigation of revegetation trials on the northern waste rock dumps using RP4 water at this time may have influenced water levels in the bores, although there was generally a good seasonal correlation in pattern between water levels in the bores and that in RP4. The concentrations of most elements were higher at the end of the Dry season than at the end of the succeeding Wet season, but the data were not otherwise distinctive. Mineralogical data for samples collected from the boreholes indicated that there was no significant alteration of the weatherable minerals (mainly chlorite, mica and hematite) that are typical of fresh waste rock (Riley et al 1993). Major and minor element analyses of all samples were reported.

In order to further clarify the issue about the nature of water flow and contaminant movement through the landform, ANSTO installed ten 200 L capacity lysimeters at different levels in a 13 m high stockpile in part of the southern waste rock landform (Bennett & Plotnikoff 1995). Five time domain reflectometry (TDR) probes were also installed adjacent to alternate lysimeters to measure the moisture content of the stockpile material. LiBr was spread over the surface of the landform to act as a chemical tracer. Non-uniformity of water flow through the landform was confirmed by the investigation, as might have been expected (Kuo 1996). Some intermediate level lysimeters did not collect any water whereas shallower and deeper ones did. The program indicated a high degree of inhomogeneity in the flow structures within the dump.

The difficulty in characterising the processes occurring in the interior of the landform has led to the formulation of an investigation that is still in progress. The years of monitoring data available for water retention ponds and groundwater at Ranger, and the outputs from recent research on stockpile runoff and the geochemistry of waste from Pits #1 and #3, provided the starting point. This database could be used to describe the hydrological and hydrochemical behaviour of the landform and to predict the likely future impacts of the landform on surface and groundwater quality. The objective has been to use a GIS-based approach (integrating water quality, rock volume, and catchment size) to determine if changes in composition of water reporting to collection sumps or in monitoring bores can be accounted for by changes in volumes of waste stored in the corresponding catchments.

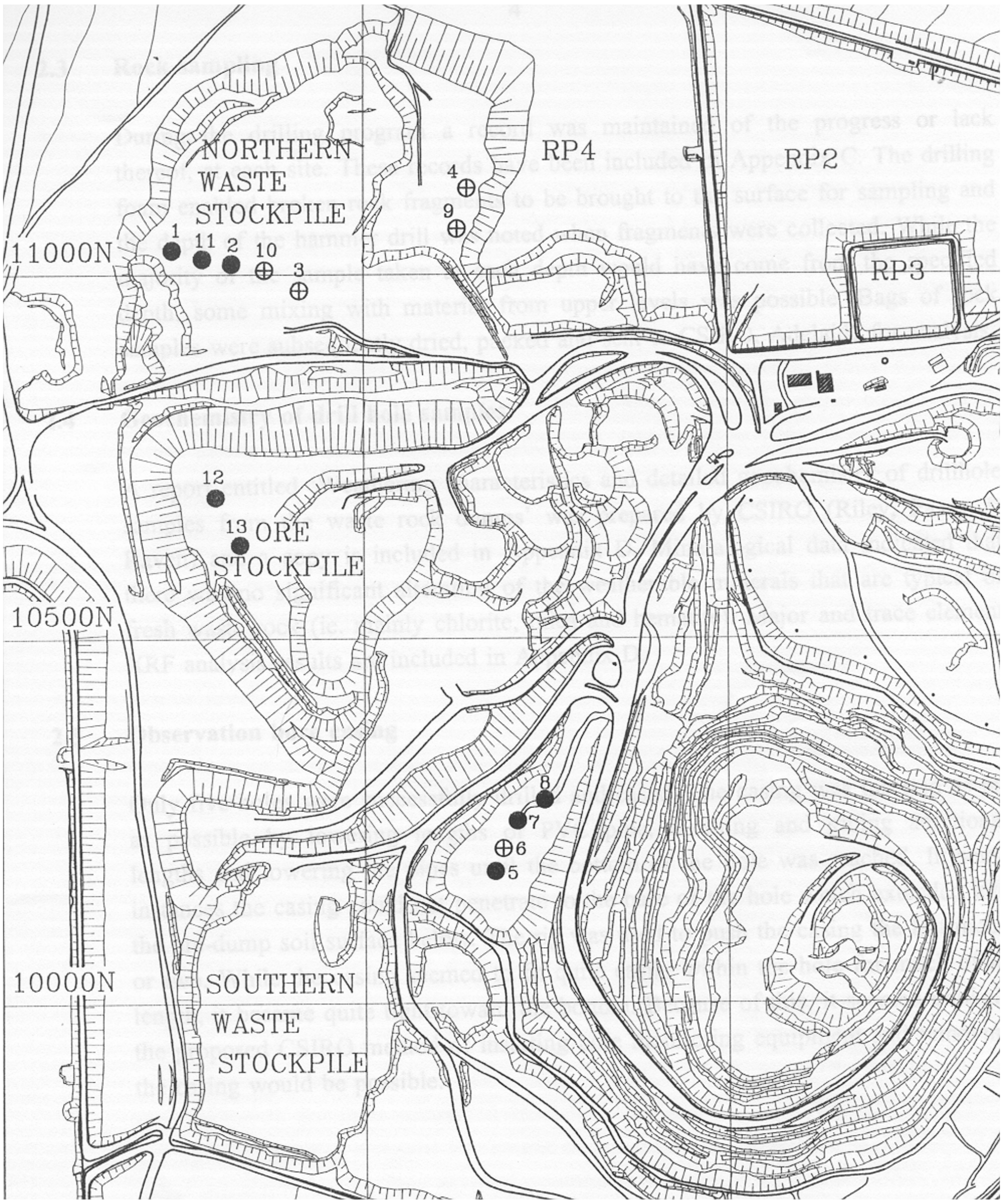

Figure 5 Location of successful (open circles) and unsuccessful (solid circles) monitoring bores drilled in waste rock and low grade ore stockpiles

5.5.7 Landscape evolution modelling

A 3-dimensional landform evolution model, SIBERIA, is being refined for use in the erosion assessment of post-mining rehabilitated landforms in the ARR. The model can also be used as an engineering tool to enable optimisation of a rehabilitated landform design to reduce erosion and increase the stability of landforms. The model was developed to examine the erosional evolution of catchments and their channel and gully nerworks. Testing and validation of SIBERIA is necessary to give confidence that predictions are reliable.

Initially, Willgoose and Riley (1993) used SIBERIA to model the Ranger Mine 'above-grade' landform using parameters derived from data collected from areas of the waste rock dump (WRD) with no vegetation or surface amelioration, such as ripping or rock-mulching. Data were collected from erosion and runoff plots on the WRD using rainfall simulation and monitoring of natural storm events. Their study showed that after 1000 y the landform would be dissected by deeply incised erosion valleys.

Willgoose (1995) conducted a desk-top sensitivity study on the evolution of the Ranger Mine post-mining landform which showed significant effects of vegetation on simulated results. The effects of surface treatments on SIBERIA input parameter values and erosion rates were studied using data from plots with various surface treatments eg unvegetated and unripped, vegetated and ripped, and rock mulched (Evans et al 1998). Natural rainfall event data from the sites were used to parameterise SIBERIA. The Revised Universal Soil Loss Equation (RUSLE), calibrated to the sites (Evans & Loch 1996, Evans 1997) predicted a total sediment loss rate of approximately 3100 t/km^2/y from the unvegetated and unripped cap site and approximately 140 t/km^2/y from the ripped and vegetated site. These values were calculated for slopes of approximately 3% and the erosion rates are orders of magnitude greater than the natural rate given in Wasson (1992). SIBERIA simulations of post-mining rehabilitated landform evolution showed that for the unvegetated and unripped case, the landform at 1000 y would be dissected by localised erosion valleys (maximum depth = 7.6 m) with deposited fans (maximum depth = 14.8 m) at the outlet of the valleys. This simulated valley form has been recognised in nature which indicates that SIBERIA models natural processes. For the vegetated and ripped case, reduced valley development (maximum 1000 y depth = 2.4 m) and deposition (maximum 1000 y depth = 4.8 m) occurred in similar locations as for the unvegetated and unripped case (ie. on steep batter slopes and in the central depression areas of the landform). For vegetated and ripped conditions, simulated maximum valley depth in the capping over a proposed tailings containment structure was about 2.2 m after 1000 years. Valley incision was approximately 5 m for unripped and unvegetated conditions. By modelling valley incision, decisions can be made on the minimum depth of tailings cover required to prevent tailings from being exposed to the environment within a time frame acceptable to stakeholders to manage impact.

Validation of the model is important to provide confidence in SIBERIA simulations. Field studies were conducted to compare SIBERIA predictions with observed erosion on both short-term and long-term analogue sites for the rehabilitated landform at Ranger Mine (Hancock et al 2000, 2002). The Scinto 6 mine, in the South Alligator River valley, was used to test SIBERIA's ability to predict erosion over a time period of about 50 years (Hancock et al 2000). Waste rock was dumped adjacent to the entrance of the cut resulting in a flat topped WRD with angle-of-repose batters and has been undisturbed since mining ceased approximately 50 years ago. Qualitatively, erosion features on the WRD at Scinto 6 are similar to that predicted at Ranger Mine by SIBERIA. During the 1996–97 Wet season runoff and erosion from the WRD at Scinto 6 were monitored. Data were collected on rainfall intensity, runoff rate and total sediment loss. These data were used to derive input parameter values for SIBERIA. Model simulations assumed initial landform conditions with non-eroded batters and simulations showed development of channels similar to those observed at the site.

A second validation study was conducted at Tin Camp Creek, a natural site in Arnhem Land, to test the ability of SIBERIA to model geomorphic development over geologic time (Hancock et al 2002). Historically the site is relatively undisturbed and the historical hydrology and erosion that shaped the landform can reasonably be assumed to be as it is today. Measured geomorphic data were used to calibrate the SIBERIA model, which was then used to make independent predictions of the geomorphology of the study site. A qualitative, or visual, comparison between the natural and simulated catchments indicates that SIBERIA can match hillslope length and hillslope profile of the natural catchments. A comparison of geomorphic and hydrological statistics such as the hypsometric curve, width function, cumulative area distribution and area-slope relationship indicated that SIBERIA simulated the geomorphology of the selected Tin Camp Creek catchments.

To date, landform evolution modelling using SIBERIA has been based on input parameter values derived from experimental data for the current WRD at Ranger Mine and remain constant throughout the simulation period. Since the period considered by the model is about 1000 years, it is necessary to take into account the change in erosion rate that will take place as a result of soil and vegetation development over that time period. The effect of temporal trends on the evolution, as a result of erosion, of the Ranger Mine post-mining landform was assessed using the SIBERIA landform evolution model. Data from various field sites with properties similar to those likely to develop on the rehabilitated landform at Ranger — the Tin Camp Creek site, Scinto 6, the batter slope at Ranger Mine, and an undisturbed site on the Koolpinyah Surface near Ranger — were used to assess temporal changes in input parameter values (Moliere et al 2002). Conditions for both sheet and channel erosion where studied and results showed that parameter values decrease rapidly, resulting in reduced erosion rates, within the first 50 years after waste rock dump construction. After 50 y erosion rates approach that of the natural, undisturbed landform. Using parameter values for each site, a sensitivity study was conducted to assess the effect of changing parameter values on simulation results.

The SIBERIA simulations conducted in the above studies were based on parameter values that represented the surface condition of the whole rehabilitated landform without any spatial variation of surface conditions, such as vegetation, ripping or rock-mulching of the landform. Initial research has been conducted assessing the effects of spatial changes in input parameter values in SIBERIA simulations (Ferguson 1999). The results of this study are currently being finalised.

The studies described above give considerable confidence that both erosion rates and landform stability of the post-mining landform at Ranger Mine can be predicted. However, there is still a need to assess a rehabilitated landform design for environmental impact. ***eriss*** has developed a method (Evans 2000), based on these studies, which can be used to predict the above background contribution that a landform will make to stream sediment loads. Water quality guidelines can be used to assess if the erosion contribution to stream loads is acceptable. The method uses SIBERIA simulations to first assess landform stability and whether contaminants are adequately encapsulated. The RUSLE is then used to determine erosion rates from the landform and a sediment delivery ratio is used to determine sediment movement through the catchment to the stream. Gulungul Creek was used as a case study and results showed that sediment loads in the stream would increase by only 1.6% above background as a result of erosion of the now discarded above-grade landform design. This technique expands the erosion modelling techniques from the mine site landform scale to the catchment impact scale and has now been applied to both Jabiluka and Nabarlek mine sites (Evans et al in prep; Grabham 2000).

5.5.8 Surface form and erosional behaviour

To, date the waste rock stockpiles have been constructed as typical terraced mine landforms in approximately 10 m high lifts with angle-of-repose batters (approximately 36o or 1:1.4). A substantial R&D effort over the years by ERA and eriss has been focussed on the erosional behaviour of the stockpiles and the conceptual design of the final landform slopes. Early studies by eriss advocated a geomorphic approach in the design of slopes on the rehabilitated landform (for example, Cull & East 1987, East & Cull 1988).

Raines (1987) reported on 1:5 experimental batter slopes, 135 m wide, constructed on the easternmost section of the northern waste rock dump. Five treatments were planned on 25 m wide plots for the full length of the batter, namely:

- vegetation cover of trees and shrubs
- bare
- hydromulch with grasses
- rock mulch
- rock mulch with vegetation cover of trees and shrubs.

In 1987, four large-scale erosion plots (Figure 5) were constructed on the easternmost batters of the northern waste rock stockpile: two were 1:3 rectilinear slopes (56 m long and 22 m wide) and two were concave hillslope analogues (78 m long and 22 m wide) with an overall gradient of 1:5 (1:3 in the upper parts grading to 1:8 in the footslope). One of each of the slopes was capped with a 30 cm-thick layer of run-of-mine waste rock while the other was capped with chlorite schist. The objective of the project was to determine the effect of rock type and slope shape on erosional stability through a number of Wet season rainfall events and thus be able to develop an optimum design for the final landform. The slopes were appropriately constructed to direct runoff onto triangular cement aprons and thence through calibrated H-flumes where probes determined the height of flow at one-minute intervals during rainstorms. Automatic water samplers collected discrete samples for chemical analysis, conductivity and turbidity. Bedload sediment was collected in troughs embedded across each concrete apron at the base of each flume. Erosion pins were inserted across each of the constructed slopes in order to provide the basis for measuring erosion or deposition.

The results from these trials have been presented in a number of reports and publications (for example, East et al 1989c). Key results are that peak discharges for the concave slopes (hillslope analogues) were consistently about half the peak discharges for the straight slopes due to generally shorter flow times, higher infiltration rates and lower runoff coefficients. Solute concentrations varied inversely with discharge irrespective of slope type or surface cover. Mean solute concentrations for runoff were in all cases higher for the two plots with the cover of chlorite schist than for plots with run-of-mine rock due to differences in the mineralogy of weathering products. Solute concentrations for late Wet season storm runoff events were generally lower than those for early Wet season storms by about an order of magnitude. Suspended solids concentrations for all plots varied directly with discharge, in contrast to the inverse relationship for solutes and discharge. The highest suspended sediment load generally coincided with peak discharge, reflecting the optimum transporting power of the discharge. Higher concentrations were recorded for straight slopes for individual storms than for the concave slopes. Significant concentrations of sand and gravel were transported only from the straight slope plots.

Subsequent studies (Unger et al 1996) involved the modelling of conceptual landform designs using the catchment-based landform evolution model SIBERIA (Willgoose & Riley 1993, 1998). Elevation was simulated over 1000 years using a mass transport (including fluvial sediment transport and mass movement mechanisms such as creep, rainsplash or landslide) model. Runoff and sediment transport data collected from experimental plots on the minesite, and rainfall simulator experiments undertaken as part of natural erosion studies on both bare and vegetated surfaces, were used to calibrate the runoff and sediment transport models within SIBERIA. A number of conceptual final landform designs were modelled in SIBERIA.

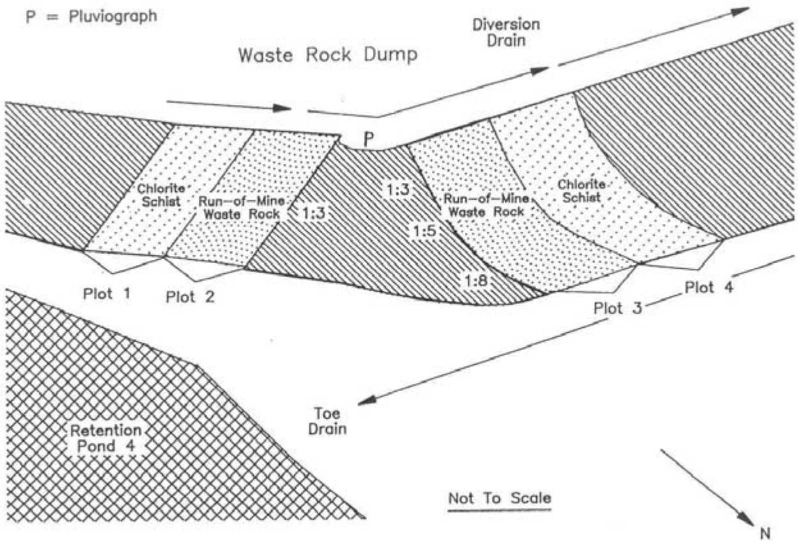

Figure 6 Details of experimental batter slopes on northern waste rock dumps

Willgoose (1995) also assessed the effects of benches on erosion using SIBERIA modelling. He concluded that:

The benches in the batters on the water shedding designs do not appear to have any substantial impact on estimated erosion. This is because convex slopes diverge flow and reduce erosion. Regions where water is spreading out are areas of low erosion risk. Regions of flow convergence are at much greater risk of erosion. Thus the centrally converging area on the original above-grade and below-grade designs were areas of high erosion.

Evans et al (1996) also reported simulations on conceptual final landform designs that were water-shedding and water-retaining. Designs with long, gentle slopes contributing flow to steeper batters triggered substantial erosion at points around the change in slope, forming localised gullies. Internally-draining water-retaining landforms that eliminate the flow to steep batters performed significantly better in the simulations. However, watered-shedding structures that concentrated flow into the centre of the structure before draining offsite all triggered deep erosion where the water was concentrated. In SIBERIA simulations, benches introduced on localised parts of the batters appeared to improve the erosion performance of the batters if they did not overflow. In all cases, vegetation had a significant affect in reducing erosion. Some subsequent field studies on the northern waste rock stockpiles at Ranger Mine involved the deliberate initiation and monitoring of gully erosion (Bell & Willgoose 1998). The results are still being analysed.

5.5.9 Dispersion of erosion products in the immediate vicinity of the Ranger mine site

The Ranger mine site tributaries (Gulungul, Djalkmarra, Coonjimba and Georgetown Creeks) are the first to receive sediment generated on the current and rehabilitated Ranger mine site and act as a buffer for Magela Creek. Djalkmarra and Coonjimba Creeks are impounded by the embankment for the mine access road and retention pond 1, respectively. Therefore, there is a low risk for the dispersion of mine site generated sediment, especially sand, through these two creeks for as long as the structures remain intact. Research has been conducted on the magnitude of sediment yields from small catchments, both undisturbed and disturbed by mining and associated activities, as well as on the fluxes and pathways for sediment transport and storage between Ranger mine and Magela Creek (Erskine & Saynor 2000).

Duggan (1985, 1988, 1994, unpublished) determined the suspended sediment and solute yields of five natural and six disturbed (mining and urban development) catchments with areas less than 61.9 km^2 in the Alligator Rivers Region, including Gulungul and Georgetown Creeks, two small catchments on the Ranger mine site and two small catchments at Jabiru. The yields for the natural catchments were low, with sediment yields being less than 34.8 $t/km^2.yr$ and solute yields less than 14.0 $t/km^2.yr$. Solute yields ranged between only 14.5 and 35.2% of the total terrigenous yield (combined suspended sediment and solute yields). The resultant denudation rates (mean landscape lowering of about 16 mm/1000 yrs) are an order of magnitude less than the typical range for the seasonally wet tropics (Saunders & Young 1983). Magela Creek at the gauging station immediately downstream of the Ranger mine exhibits even lower sediment and solute yields (Hart et al 1982, 1986, 1987b). Bedload is a relatively high proportion (48.6%) of the total sediment load (Roberts 1991), a result consistent with plot measurements at Ranger (Evans 1997, Saynor & Evans 2001). Suspended sediment samples contained a predominance of fine and medium sand when concentrations exceeded 1000 mg/L. Therefore, natural background sediment and solute yields are very low by world standards and bedload (sand) comprises a major component of the total sediment load.

Duggan (1988) found that suspended sediment concentration in the natural catchments was best correlated with peak discharge and that suspended sediment transport was dominated by large events. There was no pronounced early Wet season peak in yield or marked first flush of suspended sediment. The seasonal distribution of suspended sediment transport was dominated by large events in February and March. Therefore, there is a high risk that extreme events, impacting on a recently rehabilitated Ranger mine, will cause large scale erosion on site and will disproportionately increase sediment exports off site.

The disturbed catchments monitored by Duggan exhibited mean suspended sediment yields that were usually two orders of magnitude greater than the natural catchments. There was an exponential decline in suspended load yields with time following completion of rehabilitation. Yields decreased by one order of magnitude in the second year after rehabilitation and by two orders of magnitude by the fourth year. This rapid decline was accompanied by a marked decrease in the silt and clay percentage of the suspended sediment. Furthermore, disturbed catchments exhibited sediment exhaustion during the Wet season due to progressive flushing of the available fine-grained sediment. Mining can potentially increase sediment yields by two orders of magnitude over background values and can greatly change suspended sediment transport dynamics.

All of the material eroded from the Ranger mine site will not be transported directly and immediately off site and into the mine site creeks (Duggan 1988, Evans 1997, Erskine and Saynor 2000). Duggan (1988, 1994) found significant sediment storage on natural slopes during erosion pin measurements. Basal slope concavities are formed by deposition of the sediment eroded from upslope and are common in the Alligator Rivers Region (East et al 1989a, 1994). Evans et al (1999) also observed small scale litter and coarse organic debris dams, trapping sediment and fine particulate organic matter on burnt, vegetated plots on the Ranger waste rock dump. Pickup et al (1987) concluded that there is only limited opportunity for the dispersion of eroded sediment into the mine site tributaries because the natural slopes have a low gradient, high infiltration capacity, surface gravel lags and few rills. Sand and gravel sized sediment will not be transported far during individual events but fine sediment deposition requires very hydraulically rough conditions (ie vegetated areas) or essentially still water (ie lakes, billabongs and wetlands). The sediment delivery ratio refers to the percentage of the annual gross erosion that is measured as the sediment load at a catchment outlet. There is an inverse relationship between sediment delivery ratio and catchment area and sediment storage is usually greater than sediment yield. Duggan (1988) determined sediment delivery ratios of 0.41, 0.28 and 0.44 for Ranger (catchment area of 0.22 km^2), Nabarlek (catchment area of 0.78 km^2) and Jabiru Tributary 1 (catchment area of 0.15 km^2) catchments, respectively. Therefore, most of the sediment generated on the rehabilitated mine site will be temporarily stored there (Warner & Wasson 1992). However, the residence time of the stored sediment is unknown because it can be subjected to repeated phases of re-entrainment, transport and storage. Duggan's (1988) sediment budget for Ranger Tributary for year 2 found that sediment storage accounted for 54% of the eroded sediment. Pickup et al (1983, 1987) noted that small tributaries near Ranger are frequently poorly defined and sometimes discontinuous and that they all discharge into backflow billabongs at the junction with Magela Creek (Riley & Waggitt 1992). Warner and Wasson (1992) noted that sediment would move as event-driven pulses both within and between different fluvial landforms from Ranger to Magela Creek through the mine site tributaries. However, they did not attempt to determine the nature of this sediment routing. Cull et al (1992) found that, on Gulungul Creek, the channel and natural levees are composed mostly of sand and that silt and clay contents are low but at their greatest on the floodplain. Channels are transit zones for sand. However, they also noted that unchannelled reaches are present near the mine site and that the surface sediments contain much higher silt and clay contents. Some fine sediment storage will occur in the unchannelled valleys and on the floodplain.

Thomas and Hart (1984) and Nanson et al (1993) found that sandy plugs deposited by Magela Creek dam the backflow billabongs on the lower section of all mine site tributaries. Furthermore, these sandy plugs have deflected the billabong outlet channels down the left bank valley side in the form of a deferred tributary junction or a yazoo stream (Pickup et al 1987, Nanson et al 1993). Clearly, Magela Creek transports more sediment and has aggraded more rapidly than the tributaries. This indicates that very little, if any, sand has been transported through the billabongs into Magela Creek from the tributaries to date.

Significant local storage of the sediment generated on the rehabilitated Ranger mine will occur on site and immediately downstream. Sands will be repeatedly stored in, and reworked from, the alluvium of the tributary channels and floodplains. However, the immediate sink for both sand and mud (ie silt and clay) will be the backflow billabongs at the junction of the tributaries with Magela Creek. Essentially no sand and only minor amounts of silt and clay will be exported from the mine site tributaries and into Magela Creek, until this deposition greatly reduces the storage capacity of the billabongs. Erskine and Saynor (2000) prepared a range of potential sediment budgets for the rehabilitated Ranger mine for a 1000 year design life and concluded that it was likely that the mine site and the downstream creeks would store nearly all of the supplied sediment.

5.5.10 Dispersion of erosion products in the Magela Creek and the Magela backwater plain.

Extensive research has been conducted on the Quaternary history of Magela Creek downstream of Ranger mine and on sediment routing to the East Alligator River (Wasson 1992). This work is briefly outlined below. The Quaternary history of the sand anastomosing zone of Magela Creek outlined by Nanson et al (1990, 1993) was discussed in Section 5.5.2. The significance of this research for predicting the dispersion of mine-derived sediment supplied by the mine site tributaries is also assessed based on the review of Erskine and Saynor (2000).

The late Quaternary history of the Magela backwater plain was described by Clark et al (1992b). Five major stratigraphic units were identified overlying bedrock. In vertical sequence, these were:

1. Basal fluviatile sands and gravels;
2. A complex body of freshwater interbedded sandy clay, clayey sand, sand and gravelly clayey sand capped by a discontinuous palaeosol;
3. Early- to mid-Holocene estuarine blue grey clay containing a number of clay, peat and sandier lithofacies, which are rich in mangrove pollen and sedimentary pyrite;
4. Late Holocene mottled, oxidised, estuarine grey clay; and
5. Late Holocene dark, organic-enriched, freshwater clays.

East et al (1989b) and Clark et al (1992a) reconstructed the major sedimentary environments corresponding to these stratigraphic units. After about 8 ka, sea level rose from about -13 m AHD to near present sea level between 5.5 and 7.0 ka (Woodroffe et al 1987, Clark et al 1992a). This resulted in both the sea flooding the lower Magela valley and the first appearance of mangroves at about 6.2 ka (Clark et al 1992a). Rapid estuarine sedimentation occurred in a *Rhizophora* forest, called the 'big swamp' phase on the neighbouring South Alligator River by Woodroffe et al (1986, 1989). The mangroves retreated downstream from the Mudginberri Corridor to the Central High between 4.4 ka and 2.3 ka. As the strength of tidal connection was progressively severed, transition sediments were deposited and the former tidal channels were dismembered (Clark et al 1992a), forming the channel and floodplain billabongs of Hart and McGregor (1980) and Walker and Tyler (1984). Between about 1.5 and 1.0 ka, freshwater wetlands formed and dark clay or black soil was deposited over the bulk of the lower floodplain (Clark & Guppy 1988, Clark et al 1992a).

All of the mine site tributaries discharge into the anastomosing (multi-channelled) sand zone of Magela Creek (East et al 1993, Nanson et al 1990, 1993). Nearly all of the silt and clay, and most of the sand supplied from the mine site tributaries will be transported through this zone to the lower floodplain (Erskine and Saynor 2000). Very minor amounts of silt and clay will be deposited on the floodplain and some sand will be deposited in the bed and on the levees and the floodplain as splays (Erskine & Saynor 2000). This zone is a transport reach characterised by relatively minor sediment storage (Cull et al 1992).

The lower floodplain or backwater plain starts at Mudginberri Billabong and extends to the East Alligator River. While this area is being treated here as a single unit, there are longitudinal changes in landforms (the Mudginberri Corridor, Upstream Basin, Central High and Downstream Plain of Warner & Wasson 1992). The natural levee of the East Alligator River does not impound the lower reaches of Magela Creek (Warner & Wasson 1992) and the extensive wetlands were formed at least in part by sedimentation raising the Magela Plain above tidal inundation (Clark et al 1992a).

Cull et al (1992) investigated the surface sediment texture of the lower floodplain sediments. The upper 2 cm of Magela plain sediments were sampled at 107 locations for particle size analysis. Sediment distribution in Magela Creek is similar to an alluvial fan. Coarse sediments are deposited upstream with an increasing percentage of fine sediments downstream. Sand is largely restricted to the anastomosing section of Magela Creek, Mudginberri Corridor and the proximal part of the Upstream Basin. However, clay contents did not increase progressively downstream, indicating that side tributaries also input sediment to the floodplain. The longitudinal distribution of sediments shows that the influence of sediment from Magela Creek does not extend beyond the Central High.

Hart et al (1987b) calculated an input-output budget for the lower Magela Creek floodplain or backplain for the 1982–83 Wet season. They found:

> Broadly, the Magela floodplain appears to be a net source of the major ions (sodium, potassium, calcium, magnesium, chloride, sulfate and bicarbonate) and a net sink for suspended solids and nutrients (total phosphorus, nitrate-N, ammonia-N). The data suggest that the floodplain is also a net sink for the trace metals copper, lead and zinc, and uranium, but in these cases the amounts transported are quite small and the uncertainties rather large.

They estimated that 5400 t of suspended solids entered the floodplain, 1700 t (69% reduction) were exported and 3700 t were deposited in the floodplain. However, there are large error terms associated with these estimates.

Cull et al (1992) calculated the mean annual suspended sediment fluxes for the lower reaches of Magela Creek. Of the 9900 t/a that is delivered to the plain, only 3600 t/a are exported to the East Alligator River. This represents a 64% reduction in the inflows due to deposition and storage. However, large uncertainties are attached to the flux estimates, making it difficult to resolve a sediment budget. Despite the difference in the magnitude of the estimated sediment loads by Hart et al (1987b) and Cull et al (1992), the percentage of the inflowing sediment trapped in the Magela plain is similar for both data sets (69 and 64%, respectively). Sediment radionuclide concentrations of Magela Creek and the plain were interpreted by Cull et al (1992) to mean that about 90% of the particulate matter from Magela Creek is deposited in the first 18 km which is about 15% of the plain.

Cull et al (1992) also attempted to use ^{137}Cs as a tracer of sedimentation on the lower Magela floodplain. They encountered many problems with the technique such as unexpected spatial variability in data and uncertainties in the atmospherically derived component due to variable tree cover and unknown rates of organic matter export. As a result, they were only able to calculate an upper limit to overall sedimentation rate of <0.9 mm/yr.

Cull et al (1992) then conducted detailed analyses of the natural U and Th series radionuclides in flood water samples collected between 19 and 21 February 1985 and on 10 April 1986. They concluded that during the last 100 years there has been little but not zero loss of suspended sediment from the floodplain. A small but inter-annually variable proportion of particulates delivered to the floodplain is exported but the proportion could not be quantified with the then available data.

Subsequent work based on naturally occurring radionuclides by Murray et al (1993) found that all of the inflowing particulate load from Magela Creek and adjacent tributaries is retained by the floodplain. Similarly, a substantial fraction of solutes and colloids is also trapped.

Erskine and Saynor (2000) concluded from the above work and a range of sediment budget scenarios that the lower Magela floodplain is a relatively efficient sediment and solute trap. Any sediment and solutes eroded from the Ranger mine would be deposited and stored on this floodplain. Sediment depths will be greater at the upstream end in the Mudginberri Corridor. However, the lower Magela floodplain will be the last area to receive mine-derived sediment. The rate of sedimentation is likely to be closer to the rates of clay deposition of 0.19 and 0.20 mm/yr determined by Clark et al (1992b) by the ^{226}Ra excess method in the Mudginberri Corridor. Cull et al (1992) estimated a mean deposition rate of 0.23 mm/yr based on all radiometric methods. Thomas and Hart (1984) calculated a sedimentation rate of 0.43 mm/yr in the Mudginberri Corridor based on a single radiocarbon date. Little but more likely no mine-derived sediment will reach the East Alligator River.

While a disproportionately large effort has been directed at understanding the evolution and behaviour of the sand anastomosing reach and lower floodplain or backwater plain of Magela Creek, these areas clearly will not be the initial repositories for mine-derived sediment. The mine site tributaries are not as well understood but are certainly more important sediment stores and sediment pathways for particulates eroded from Ranger mine. The reason for this discrepancy in research effort is that the lower Magela wetlands are internationally significant and have, therefore, been perceived as being the most important ecosystem likely to be impacted by mining. Under Erskine and Saynor's (2000) most likely post-rehabilitation sediment budget scenario, no mine site generated particulates are likely to reach the lower Magela wetlands. No further research is needed on the Magela backwater plain.

5.5.11 Erosion issues at Jabiluka

Ngarradj is a major downstream right-bank tributary of the Magela Creek which flows directly into the Magela Creek floodplain. The Magela Creek and floodplain are listed as Wetlands of International Importance under the RAMSAR Convention and recognised under the World Heritage Convention. The catchment of Ngarradj contains the site of the Jabiluka uranium mine where portal construction has occurred and will be the first catchment to be affected should any impact result from mining operations at Jabiluka. The Draft Environmental Impact Statement (ERA, ERA Environmental Services & Kinhill Engineers 1996) for underground uranium mining at Jabiluka proposed milling the ore at the existing mill at Ranger. However, following the refusal of the traditional land owners to permit the movement of ore from Jabiluka to Ranger, the Jabiluka Mill Alternative (JMA) was developed and approved by the Commonwealth Government in August 1998. This alternative stipulated that all mill tailings had to be returned to the underground mine void and to specially constructed stopes or silos instead of tailings pits, as proposed by ERA (Johnston & Prendergast 1999).

To assess physical impact on the streams within the Ngarradj catchment, gauging stations were installed in 1998 upstream (Upper Main – UM; East Tributary – ET) and downstream (Swift Creek – SC) of the mine to assess before and after impact. At each gauging station, rainfall, stage, EC, pH and turbidity measurements have been taken at 6 minute intervals. A stage activated pump sampler was installed at each gauging station to obtain a 'continuous' suspended sediment data set throughout the Wet season hydrograph. Suspended sediment grab samples and bedload samples were also taken weekly during the period of flow. The design is that any change occurring at the downstream site (SC) not observed at upstream sites (UM and ET) indicates that the source is from the western part of the catchment where the mine is located. In addition to the gauging stations, permanent cross sections have been installed throughout the catchment and are surveyed each Dry season to assess change in stream profile and bed material size distribution. Erosion pins and scour chains have also been installed on the mine site tributaries and at the gauging stations to determine bank erosion rates and depths of scour and fill during the Wet season. A continuing monitoring program is presently being implemented based on partitioning of the annual hydrograph into rising, steady state and falling stage. To complete the coverage of the catchment a study is being commenced to collect baseline data on sediment distribution on the alluvial fan downstream of the SC site and the backwater plain of Ngarradj at its confluence with Magela Creek. Further analysis is being conducted to determine the cause and impact of changes in stream profile and sediment concentration observed during the monitoring program

Construction of proposed silos at the Jabiluka mine for underground storage of tailings will result in above-grade waste rock dumps (WRDs). The WRDs will be located in small subcatchments to the west of the main Ngarradj channel and it is likely that erosion products from the WRDs will eventually enter the main Ngarradj channel downstream of the mine. An impact assessment of WRD erosion on Ngarradj (Evans et al in prep) was completed using a combination of the RUSLE, a simple area-discharge relationship and stream sediment load data. Monte Carlo simulations of the RUSLE and discharge equations indicated that a mean stream sediment concentration increase of about 8 % or 2.8 mg/L (*SD* = 3.1 mg/L) at the SC site was expected from construction of the mine's WRDs. The model indicated that there was only a very low probability that mine activity would result in exceedence of the water quality guidelines for stream suspended sediment. To strengthen this assessement, rainfall simulation studies were conducted on the mine site in 2001 to obtain site erosion data. Analysis of the rainfall simulation data is presently being finalised.

Erosion research relative to Jabiluka is aimed at applying the landform evolution model, SIBERIA, on a catchment-wide basis to assess rehabilitation proposals for the mine site. The project focuses on the development of a GIS tool called ArcEvolve and aims to provide a quantitative risk assessment tool that uses a combination of landform evolution modelling and basin analysis in a GIS framework (Boggs et al 2001). The system allows pre- and post-impact comparison of catchment geomorphic statistics such as width function, hypsometric curve, cumulative area diagram and area-slope relationship. The geomorphometric measures confirm that little change occurs in the undisturbed catchment over 1000 years. Future work in this project will use field data from disturbed areas of the mine site to assess possible mining impacts on a catchment wide basis.

5.5.12 Erosion issues at Nabarlek

Decommissioning work and rehabilitation at the Nabarlek minesite were completed at the end of 1995. Tailings were buried in the mined-out pit and capped with waste rock. An erosion assessment of the cap design, using a combination of modelling and analogue estimates, indicated that denudation rates on the cap would be < 0.1 mm y^{-1} (Riley 1995). Riley (1995) observed that roads were areas of most severe rill development in the Alligator Rivers Region (ARR) and suggested that rill development (0.2–0.3 m depth) on the pit cap would occur in the early stages of adjustment toward equilibrium but not persist in the long-term.

As a result of a request for final approval of the revegetation at the minesite an erosion assessment of the site was conducted by ***eriss*** in August and October 1999 and the results presented at the Nabarlek Rehabilitation workshop (Evans et al 2001). It was concluded that unsealed roads are the areas of most serious gully erosion. This can extend to any site where the fragile sandy soils have been disturbed ie. in constructed drains and at the western end of the airstrip. Once vegetation has been removed, incision quickly occurs and it is likely a gully will develop. An example of this exists in nearby woodland where a vehicle track has been deeply incised to several metres wide and > 1 m deep with vertical walls and now appears to be a seasonally-flowing watercourse debouching into Buffalo Creek.

An impact assessment of the site using the technique of Evans (2000) was completed using erosion predictions derived using the RUSLE (Grabham 2000). The site was classified into erosion units depending on surface treament, slope and erodibility and total erosion was derived. A sediment delivery ratio was applied to determine the amount of eroded soil that would reach nearby Cooper Creek and this was assessed against background sediment concentrations in the stream. Results indicate that, under present conditions, there may be elevated sediment loads in the seasonally-flowing small tributaries but in Cooper Creek sediment concentrations will not be elevated above water quality guidelines.

5.5.13 Issues for future work

Geomorphic stability of the Ranger mine site and the Magela Creek

There are two additional projects that should be undertaken to improve assessments of the geomorphic stability of the Ranger mine site. These relate to the magnitude and frequency of extreme events and their erosional effects on Magela Creek next to pit 3 and have been modified from Erskine and Saynor (2000).

Firstly, slackwater deposits should be combined with an appropriate hydrodynamic model to reconstruct Holocene palaeofloods on the East Alligator River and Magela Creek in the sandstone gorges. Alternatively, the probable maximum precipitation and resultant probable maximum flood should be calculated by an accepted method for Magela Creek at the mine site (Nathan & Weinmann 2001) and the corresponding flood heights and velocity distribution should be determined by an appropriate hydrodynamic model (say HEC-RAS or MIKE 11) for a 1–2 km reach of Magela Creek next to the mine.

Secondly, the role of such catastrophic floods in causing channel avulsions and large scale bank erosion on Magela Creek next to the Ranger mine should be investigated so that the risk of Magela Creek eroding pit 3 can be determined.

Erosion of rehabilitated landforms

Research has focused on development of the SIBERIA landform evolution model for assessment of post-mining landforms. Issues addressed include determination of methods to collect site data to derive model input parameter values; assessment of the effects of WRD surface treatments on model output; validation of model processes; and refinement of simulations by incorporation of temporal and spatial variation in input paratmeter values.

Current research expands the model application from a mine site basis to catchment-wide impact assessment applications. The modelling technology has been incorporated in a GIS and uses geomorphic statistics to assess impact. A prototype is being developed for the Ngarradj catchment and future assessment of Jabiluka will be conducted using field data from the mine site. To further test the technology, the Nabarlek mine site will be used as a case study for impact assessment based on landform evolution simulations using the ArcEvolve software developed in the Jabiluka GIS project. There is also a need to conduct a reliability assessment of SIBERIA simulations to provide probability distributions of model outputs. A project is planned to develop technology to incorporate Monte Carlo simulations in SIBERIA simulations. This is a technically difficult project and details of the project are still being finalised.

In the future, the refined erosion modelling technology will be used as a design tool to work with ERA to assess actual final landform proposals and optimise the final landform design in accordance with BPT principles.

Dispersion of erosion products in the immediate vicinity of the Ranger mine site

The mine site tributaries will be the first to receive sediment generated from the rehabilitated mine site and should store large amounts of the supplied sediment for a relatively long period of time. Erskine and Saynor (2000) recommended that a geomorphic and hydrologic monitoring program should be implemented which includes streamflow, suspended sediment and bedload transport and water quality at gauging stations located upstream and downstream of the mine site. In addition, geomorphic characterisation of the channel and floodplain in homogeneous reaches, the installation and periodic resurvey of permanently marked channel and floodplain cross sections, and characterisation of channel and floodplain sediments should be assessed. Historical channel changes based on the complete coverage of vertical air photographs should also be determined to identify sites of long term (~30 years) stability, erosion and deposition. The probability of gully initiation on unchannelled reaches and the sediment yields produced by such gullying also require quantification.

Dispersion of erosion products in the Magela Creek and the Magela backwater plain

No further geomorphic research is needed on the Magela backwater plain.

Erosion issues at Jabiluka

Research in the Ngarradj catchment has resulted in implementation of a monitoring system to assess physical impact, arising from the Jabiluka mine site, on the stream system. This system assesses the channelled section of the upper catchment. Three years of data are available and now methods are being developed to assess and determine the cause of change in this complex and dynamic system. Monitoring will continue, on a reduced level, each Wet season to assess change. Catchment wide coverage will be completed by commencement of a project to collect baseline data on the lower reaches of the catchment extending to the catchment confluence with Magela Creek. The braided alluvial fan and backwater plain of the lower reaches are the sinks of transported sand and mud respectively. The project will map the form of the backwater plain and alluvial fan; determine the spatial distribution of sediments and depositional areas; and map flow velocity vectors in depositional zones.

Erosion issues at Nabarlek

The following research proposals were presented to the Nabarlek rehabilitation workshop: (i) undertake a detailed assessment of erosion on the site and the likely impacts on the external environment; (ii) assess the use of airborne and field gamma spectrometry in assessing erosion and sediment transport; (iii) implement a study to assess the rate of infilling of the sedimentation pond and the effects of the sedimentation pond breach and radionuclide transport on the environment; and (iv) determine the influence of the airstrip on local hydrology and its effect on minesite landform stability.

The erosion impact assessment study has been completed as described in Section 5.5.7.

The study to assess the use of airborne and field gamma spectrometry in assessing erosion and sediment transport was implemented as a student project but not completed. Both this project and the project relating to the sediment pond will be reassessed and included in the work plan as time and resources permit.

The project addressing the hydrology of the site will be commenced in 2002 but will not focus on the airstrip. The project will develop a hydrology model for the catchment under both pre- and post-mining conditions and assess changes in catchment hydrology. This project will be closely linked to the project describe above which will use Nabarlek as a case study for impact assessment based on landform evolution simulations using the ArcEvolve software developed in the Jabiluka GIS project previously described.

5.6 Revegetation

5.6.1 Introduction

As stated previously, the primary goal for the rehabilitiation of the Ranger mine site is that the operating company must rehabilitate the Ranger Project Area ‘to establish an environment similar to the adjacent areas of Kakadu National Park such that, in the opinion of the Minister with the advice of the Supervising Scientist, the rehabilitated area could be incorporated into the Kakadu National Park.’ The major objective specified for revegetation is ‘revegetation of the disturbed sites of the Ranger Project Area using local native plant species similar in density and abundance to those existing in adjacent areas of Kakadu National Park, 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’. The revegetation programs of ERA and ***eriss*** have been directed at obtaining the knowledge required from fundamental research and practical on-site trials to achieve the rehabilitation goal and the revegetation objective.

The ERA revegetation research program began in the mid-1980s. Some of the earliest rehabilitation strategies developed by consultants at Rum Jungle (Forster 1987) and recommended for use at Ranger (Dames & Moore 1986) involved mining natural soils. These were to be placed so as to provide a cover in which to establish vegetation on clay and rock layers which cap and seal waste rock dumps, below ore-grade stockpiles and tailings. However, Fitzpatrick (1986) identified several distinct groups of minesoils that had formed on waste rock stockpiles at Ranger within a time span of about 5 years in response to high weathering rates and enhanced biological activity. Subsequent studies examined minesoils in greater detail, compared them with natural undisturbed soils in the area, assessed their fertility and stability as media for the establishment and long-term growth of native flora, and identified biological factors such as the type and distribution of rhizobia and mycorrhizal fungi that could enhance their stability.

Early glasshouse bioassays examined microbiological and nutritional characteristics of the Ranger minesoils and compared them with undisturbed natural soils. These micro-organisms were absent or poorly represented in stockpiled natural topsoils, very young minesoils (six months old) and other minesoils with no vegetation cover. However, some of the older minesoils supporting experimental plantings had similar populations of symbiotic micro-organisms to those found in the undisturbed natural soils. In terms of seedling growth, all the minesoils were more fertile than the natural undisturbed soils and the stockpiled natural soils.As well, P-deficiency was one major limitation on plant growth in natural and stockpiled soils. These early findings detremined the direction of the ERA research program on revegetation.

The revegetation research program at ***eriss*** ran from 1990–1994. The program was extensively peer-reviewed and received widespread acceptance from key terrestrial vegetation scientists before being implemented in 1990 (Ashwath 1990) and subsequently to various mining interests (eg Ashwath 1992).

The research program was not supported in full by the 1994 review of research directions at ***eriss*** (Barrow et al 1994). Based on information supplied to the review team, it concluded that as there was very little cooperation between the revegetation program run by the mining company and that run by ***eriss*** that the latter be given ‘very low priority’ as there was ‘very low probability that the results will be used.’ On the basis of this review, the Supervising Scientist decided to phase out ***eriss*** research on mine-site revegetation. It was agreed that the Office of the Supervising Scientist would maintain a watching brief on the revegetation research being undertaken by the company and its consultants and to identify further directions where necessary.

A review of the major projects undertaken by ***eriss*** between 1990–1994 is included in the summmary given in subsequent sections but it should be noted that, due to the truncation of the program, some of the results obtained have not been published.

5.6.2 Herbarium collection for the ARR

A herbarium was established at ***eriss*** circa 1980 and expanded in 1984 with the incorporation of specimens held by Parks Australia (then ANPWS) and Ranger. Specimens held by Pancontinental were lodged in the herbarium collection at the UNSW with duplicates being added to the ***eriss*** collection over subsequent years. Specimens collected during specific field exercises and other projects were regularly added to the collection with many duplicates also being lodged at the herbarium maintained by the Parks and Wildlife Commission of the Northern Territory (PWCNT). A comprehensive database of specimens was developed with regular reports being produced, culminating in the publication of an annotated checklist of the vascular plants (comprising 1899 taxa) of the region (Brennan 1996a). This includes information on the life-history of all taxa, identification of species with conservation significance as well as naturalised exotics. In 2000 a decision was made to donate the entire collection to the PWCNT in recognition of the value of the collection and the effort needed to curate this.

5.6.3 Biology of native plants

The major vegetation assemblages of sites with similar topographical features or soil properties to areas that required revegetation were described in a quantitative manner. This provided a more systematic basis for selecting plants for revegetation and for assessing the success or otherwise of revegetation. Ten sites within the Ranger project areas were surveyed as well as six sites elsewhere with similar landforms and three with similar soils. Within each site the presence of trees/shrubs (>1.5 m) and understorey species were recorded along with the above ground biomass of annual and herbaceous species. Preliminary analyses are presented in Brennan (1992), Ashwath (1994) and Brennan (1998). Analyses of the attributes recorded at these sites identified three different potential models (lowlands, rocky hills and schist hills) from which revegetation strategies and standards could be developed. Initial analyses only were completed for species richness, density and composition for all sites and for above ground biomass of annual and herbaceous species. The data could also be used to assess the effect of burning on the plant species.

To complement the information on species occurrence and density an analysis of the flowering and fruiting patterns of major groups of plants in natural habitats was undertaken using the same sites and information obtained in other studies. Annual herbaceous species, grasses, trees and shrubs were included with the results being presented in Brennan (1996b). This includes diagrams showing the flowering and fruiting records of 288 species. This information can be used to develop strategies to collect seed or for enhancing growth of selected species.

The collection, processing and storage of native plant seeds was investigated as suitable supplies of most were either not available from commercial sources or were not considered suitable. Seeds from 593 sources (representing 180 shrubs, 135 forbs, 129 trees, 8 grasses, 24 vines, 12 sedges, 5 palms and 20 others) were collected and stored with detailed data on the site/location and seed weight (and number per 10 g) being recorded in a database. A summary list of the taxa collected is provided in Ashwath (1994). The seeds are stored in a cold room – a decision on their future storage and/or use is needed.

As the usage of native plants for revegetation was also constrained by inadequate knowledge of seed germination and particularly means of breaking dormancy a number of studies to develop strategies to treat selected species were conducted. These involved determining germination percentages for a wide variety of species (Ashwath et al 1998) and specific investigations to improve germination in species that had < 50% germination. The results of pre-germination seed treatments were reported by Ashwath et al (1994a) and McIntyre et al (1994) and summarised in Ashwath (1994).

5.6.4 Characterisation of mine soils for plant growth factors

A comparison of mine soils with natural soils was undertaken to ascertain the suitability of the former for establishing native plants and for identifying possible chemical constraints. This investigation also included sample sites at Coronation Hill and Narbalek. These investigations were designed to compare the chemical properties of mine spoils with those of natural soils and to assess the ability of the former to support growth and the long-term viability of native plants. It was intended to use the results to address specific chemical inhibition of growth as well as identify soils that could be used to promote growth (Ashwath 1994). Results from pH, salinity and electrical conductivity are presented in Ashwath (1994). Preliminary conclusions covered salinity, nitrogen and phosphorus differences (Cusbert et al 1993). The mine soils at Ranger contained higher amounts of magnesium and sulphate than the natural soils of the Region and could possibly inhibit growth of plants that normally grew in less saline soils. Further, the exchangeable ionic capacity of the mine soils differed from natural soils, particularly due to the dominance of magnesium over calcium. Importantly also, the mine soils contained less nitrogen and carbon than natural soils, confirming the need to look further at the source of nutrients, in particular the role of rhizobia in revegetation. In contrast, phosphorus concentrations were higher in mine spoils and raised the possibility that some plant taxa may be inhibited by these levels.

The mineral composition of selected native plants was also investigated with leaf samples being collected from natural habitats and mine sites across the region. Some 60 species of trees, shrubs, herbs and grasses were included. The results have not been presented.

5.6.5 Symbiotic micro-organisms

CSIRO had identified the need to develop procedures as part of the rehabilitation strategy at Ranger to ensure that appropriate symbiotic organisms were present in minesoils for rapid plant establishment and growth. However, at the time there was very little information available on the symbiotic requirements of most northern Australian plants. Consequently, CSIRO set out to determine the rhizobial and mycorrhizal requirements of plants from the Jabiru region which could have potential in revegetation strategies at Ranger (Fitzpatrick et al 1989).

While only seventy two plant species were surveyed (representing only 5% of the flora recorded in the Kakadu region), it was concluded that the majority of the plants occurring in woodland and rainforest communities in the region were dependent to varying degrees on associations between their roots and soil micro-organisms for effective nutrient acquisition (Reddelll & Milnes 1992, Malajczuk et al 1994). Reddell & Joyce (1989) recognised that revegetation techniques used at that time at Ranger and elsewhere in Australia (Foster 1986) adversely impacted on populations of symbiotic micro-organisms. For example, infection of roots by these beneficial microbes may be absent, reduced or delayed in disturbed topsoils (both fresh and stockpiled) and minesoils. They suggested the concept of ‘ecological islands’ where seedlings of a range of plant species, inoculated in the nursery with appropriate symbiotic associates, could be established at strategic locations on the final landform. It was suggested that these islands could provide centres of biological diversity in the landscape with the progressive introduction of soil organisms essential to establish nutrient cycles and act as vectors to spread seed and symbiotic micro-organisms.

Given low concentrations of nitrogen in many mine soils and the importance of this nutrient for plant growth the importance of rhizobial-mediated nitrogen fixation was investigated by ***eriss***. This included the collection, isolation and maintenance of rhizobia from disturbed and undisturbed soils. Sixty seven leguminous species from the region were examined and rhizobia containing nodules collected and used to isolate the rhizobia. Approximately 500 pure strain isolations were made. Long-term storage of isolates was also investigated. McInnes and Ashwath (1992 a,b) provide information on the isolates and the techniques used. The collection was later transferred to CSIRO and the University of Western Sydney to ensure its continued usefulness. Glasshouse trials were used to select effective strains of rhizobia for a range of leguminous plants that were identified as likely species for revegetation purposes. In general the acacia species were more effectively nodulated with isolates from acacias than they were from the non-acacias (Yonga 1996). Careful selection of innoculant strains was recommended if the target species are to achieve rapid establishment when introduced into soils low in nitrogen.

A further project examined the association of native plants with mycorrhizal fungi and isolated pure strains of mycorrhiza that could be used in mine site revegetation. Soil samples were collected from both disturbed and undisturbed sites in the vicinity of Ranger, Nabarlek, Coronation Hill and Jabiluka mine sites. The samples covered a range of landforms and vegetation assemblages given the expected range of plants that could eventually be included in mine site revegetation. A number of novel techniques were adapted to isolate as many vesicular arbuscular mycorrhizal (VAM) fungi as possible (Brundett et al 1996 a,b). The soil samples were assessed for mycorrhizal species diversity and number of spores per unit soil weight.

The number and diversity of the VAM fungi differed from one habitat to another (Brundett et al 1996 a,b). The most disturbed sites were characterised by fewer numbers of VAM spores and species. Well-vegetated mine site soils contained large numbers of spores of *Acaulospora*, suggesting that they may establish well in early successional habitats. The abundance and distribution of spores and species across habitats and in relation to plant abundance were also being addressed. Preliminary statistical correlations involving soil properties and mycorrhizal bioassays suggest that VAM fungi were more prevalent in sites that had better water storage, higher organic matter, finer texture, higher pH and higher available nitrogen or potassium. VAM fungi spores were more abundant in fine textured soils, and their density and diversity was positively correlated with organic matter, phosphorus, nitrogen and iron concentrations in the soils. About 600 root samples representing 150 native plant species were collected to assess their mycorrhizal infectivity.

The significance of host plant and phosphorus nutrition on mycorrhizal propagule production was assessed in two experiments. VAM fungi formed in all experimental plants although the effect of plant species on infection or total spore production was not clearly established.

5.6.6 Plant-soil interactions

In response to the almost unquestioned use, at the time, of introduced grass species to abate dust and to minimise soil erosion on mine sites the growth performance of 10 native grass species on mine spoil at Ranger in the presence/absence of gypsum was investigated (Ashwath et al 1994b, Gray & Ashwath 1994). The results showed that some native species, eg *Setaria apiculata*, could produce similar or even better ground cover than the introduced rhodes grass (*Chloris gayana*). Further, most of the native species did not require applications of gypsum to achieve maximum growth; they had a tendancy to regenerate readily after establishment and then grow less vigorously than rhodes grass, thus competing less with native tree and shrub species that were usually established after the grass cover.

The effects of Mg:Ca ratio on growth and physiology of native plants was investigated at Ranger given that high Mg concentrations had been shown to contribute to changes in floristics on serpentine soils (Ashwath 1994). Both leguminous and non-leguminous species were grown with five Mg:Ca ratios and with and without nitrogen fertiliser. The non-leguminous species grown with fertiliser grew well. The leguminous species grew well in both fertilised and unfertilised treatments. Increased Mg:Ca produced variable results.

The effect of $MgSO_4$ on the germination of native plant species was also investigated at Ranger using native grasses, herbaceous legumes, shrubs and trees (Malden et al 1994). As with the growth experiments these results were variable with some species being greatly more tolerant to increased concentrations of $MgSO_4$. These results raise some interesting questions for revegetation procedures that rely heavily on the distribution of mixes of seeds from many species without knowing their relative tolerance to saline soils.

A number of trials relating to the use of native grasses have been undertaken by ERA, as summarised by Lane (2000), but none of these were undertaken in 'minesoils' on waste rock stockpiles.

5.6.7 Faunal recolonisation of revegetating waste rock landforms

The role of ants and other invertebrates in mine site restoration was undertaken in 1992 around the Ranger mine site and at other sites covering a range of habitats and extent of disturbance. Ants were the dominant invertebrate groups with disturbed sites having fewer species than natural undisturbed sites (Andersen & Sparling 1997, Andersen et al 1998). Rates of seed removal from the sample sites were also examined, although the results showed significant variability. Recommendations were made about the potential to use ants as indicators of further success in rehabilitation.

Studies between 1996-98 investigated how vertebrates and invertebrates recolonised six experimental revegetation sites on the northern waste rock stockpile at the Ranger mine (Corbett LK 1999). The sites included the rainfed (January 1992) and irrigation (October 1992) trial sites established by CSIRO, a trial utilising topsoil (1991) and several older revegetation trials established by Ranger Mine (1982–1986). A total of 89 vertebrate species (41 birds, 16 mammals, 16 reptiles, 16 frogs) and 23 invertebrate groups were recorded. Total species richness and abundance of all faunal groups were greater in the older sites. The data indicate that most vertebrates had colonised the revegtated areas of the waste rock stockpile within 5 years.

Recapture rates of ear-tagged individuals indicated that populations of Pale Field-rats (94/ha), Grassland Rats (13/ha) and Northern Brown Bandicoots (5/ha) were of high density, resident, breeding at a similar or greater abundance compared to populations in forest and riparian habitats at control sites elsewhere in the region. Other species (Northern Quoll, skinks, frogs, Partridge Pidgeon, Bush Stone Curlew) were also breeding, which suggests that most were residents rather than itinerants.

Vertebrate fauna diversity (defined in terms of richness, abundance and distribution) in revegetated areas of the northern waste rock stockpiles was similar to natural undisturbed control sites in the surrounding savanna woodlands. In fact, the diversity of frogs, native mammals and invertebrate groups was relatively greater on the waste rock stockpiles. The major reasons could include the close proximity to the natural undisturbed sites from which colonisers could originate, good connecting wildlife corridors, the lack of recurring fires and thus preservation of habitats all year, and good feral animal control to minimise predator impacts on founder populations.

Overall, the data collected by Corbett LK (1999) indicated that the array of vertebrate fauna living in the revegetated areas of the waste rock stockpiles was typical of that found in similar habitats of Kakadu National Park. The absence of possums and other arboreal groups was probably due to the absence of extensive stands of mature trees with hollows. Such habitats are expected to develop over time. The prognosis for the rehabilitation strategy being developed by ERA is that rehabilitated landforms are likely to be colonised with representative populations of vertebrates and many invertebrates within five years of decommissioning.

5.6.8 Trials under rainfed conditions on the northern waste stockpile

CSIRO (Reddel et al 1992) undertook investigations at Ranger to define the inputs necessary to rapidly establish resilient woodland ecosystems, incorporating native flora and fauna, on the waste rock stockpiles. The investigations focussed on identifying those functional groups of organisms that were likely to be critical in ensuring vegetation establishment and facilitating the development of minesoils from waste rock materials (through processes such as nutrient and organic matter cycling). Trials were initially established by planting tubestock directly into waste rock (minesoil) under rainfed conditions. They included establishment of ecological 'islands', in order to look at the requirements for:

- introducing mycorrhizal fungi and/or soil animals to facilitate rapid establishment and development of young woodland ecosystems;
- assessing the effectiveness of constructed 'ecological islands' as centres for colonisation of surrounding areas by symbiotic microorganisms, soil animals and plants; and
- determining the interactive effects of plants, mycorrhizal fungi and soil animals on the development of soil profiles in waste rock materials.

Tubestock included seedlings of 14 species indigenous to the Jabiru area. Ectomycorrhizal plant genera were inoculated with thick suspensions of spores from a *Pisolithus* species. VA-mycorrhizal plants were inoculated with a 'shotgun' mixture of 6 spore types collected from the Jabiru area. The areas outside each 'island' were sown with a seed mixture of 20 local woodland tree species.

Nitrogen fixation, organic matter accumulation and ecosystem development were the objectives of a second trial in which the effects of addition to the seed mix of aggressive and non-aggressive Acacia species and a perennial shade-intolerant grass were investigated on:

- the accumulation and form of soil organic matter;
- accretion of N through symbiotic fixation; and
- growth and development of the plant community.

In a third trial, the effects of vegetation on minimising erosion by stabilisation of slopes and surfaces was investigated. In this case, the role of 'islands' of planted vegetation in reducing erosion was studied, as well as the dispersion of plants on 'worst case' angle-of-repose batter slopes.

During monitoring (3 months, 6 months and 15 months after planting) (Reddel et al 1994a), one significant observation was that nutrient deficiencies (especially N deficiency) occurred in some plants. Two applications of an NPK fertiliser were applied at low rates to the trials 3 months and 15 months after establishment. In the rainfed trials, plant survival was approximately 80% and there was no statistical difference between survival rates of plants inoculated with mycorrhizal fungi and those that were not. There were marked differences between individual species in their survival rates: for example only 10% of *Callitris* survived the first Dry season whereas almost 90% of *Grevillea* and more than 75% of all *Eucalyptus* spp. seedlings survived. Growth rates of most species were generally acceptable for the conditions prevailing on the waste rock stockpiles. Minesoil analyses indicated clear differences on a seasonal basis. Samples in some plots in the Wet season were highly acidic but pH values were not as low in the Dry season. Levels of total C and N were very low. Analyses of plant tissue from 5 species did not reveal any unexpectedly high or low concentrations of nutrients or potentially toxic elements. Seed quality was poor and germination was correspondingly low.

Further monitoring of the trials was undertaken 15 months (April 1993) and 46 months (November 1995) after establishment (Lane 1996). The survival of all species combined was found to be higher for plants that were not inoculated with mycorrhizal fungi. In the case of *Acacia* species, the survival of inoculated plants was less than half that of plants that were not inoculated. In addition, the height and diameter of Acacia species treated with mycorrhiza was less than half that of untreated acacia. However, a few species (*Petalostigma pubescens* and *Eucalyptus porrecta*) had higher survival rates when treated with mycorrhiza. For species other than *Acacia*, survival across treatments did not significantly decrease between April 1993 and November 1995. However, survival of acacias decreased from 64% in 1993 to 36% in 1995. Survival of *Eucalyptus* species was high.

5.6.9 Trials under irrigation on the northern waste stockpile

Two trials were established in waste rock in October 1992 using irrigation with RP4 water (Reddel et al 1994b). The first of these was established using tubestock and aimed to assess the effects of mycorrhizal inoculation on seedling growth and the density of nitrogen-fixing *Acacia* on plant growth, vegetation community development and site N status. The second trial was designed to examine the effects of two seed mixes on plant community development, and the accretion of C and N within the soil profile. As in the rainfed trials, seed from a total of 22 species of native trees and one cover grass (*Chloris gayana*) was obtained from Ranger. Seedlings were germinated, inoculated with mycorrhiza and prepared for planting out at CSIRO laboratories in Townsville.

The experimental area was irrigated regularly by large overhead sprinklers with water from RP4 from October to November 1992, and then again from May 1993 after the Wet season. As nutrient deficiency symptoms had been observed in some plants in the rainfed trials, an NPK fertiliser was applied to all irrigated trial plots in May 1993.

Initial monitoring (Reddel et al 1994c)undertaken in May 1993 (about 7 months after establishment) indicated that in the first trial, survival rates of tubestock planted directly into waste rock (minesoil) were high, averaging 80%. There were no significant effects of treatment on overall survival or on growth (average height and diameter). However, there were differences between species in their growth and survival rates. In the second trial, there were no differences in average numbers of seedlings of tree and shrub species in either of the two treatments in which different seed mixes were applied. However, there were minor difference in species composition between the treatments, with higher numbers of eucalypts and low numbers of acacias being found in the 'standard' seed mix compared to the 'standard + acacia + grass' mix.

No discernible differences in soil development were detected from analyses of samples taken before trial establishment and at the time of monitoring about 7 months later. As in the case of the rainfed trial area, some minesoil samples had an acid reaction (pH down to 3.9) due to sulfide degradation, but this was more evident at the end of the Wet season in April 1993 than at the end of the Dry season (September 1992). In addition, EC values and the concentrations of soluble salts were substantially higher in samples collected in September 1992 than in April 1993.

Monitoring by Lane (1996) in 1995 (37 months after establishment) indicated that survival and growth rate in species groups in the irrigated and rainfed trials, regardless of mycorrhizal inoculation, was not significantly different.

5.6.10 Trials on the southern waste stockpile

The above mentioned trials had established the feasibility of establishing tubestock of native woodland species in waste rock stockpiles without the requirement for topsoil. A number of subsequent revegetation trials were established on the southern waste rock stockpile to investigate the potential for routinely establishing woodland vegetation using seed (Spain & Reddel 1995). The overall objective was to develop operationally feasible and cost-effective strategies for optimising vegetation establishment in minesoils on waste rock stockpiles. A number of trials were designed, including:

1. vegetation establishment on the near-level upper surfaces of the stockpiles to:
   - compare establishment and growth of selected species on two rock materials differing in hardness and capacity to supply nutrients;
   - assess the effects of non-aggressive *Acacia* species on establishment and growth of the plant community;
   - determine the rate of self thinning in high density Eucalyptus planting; and
   - determine the effects of two levels of application of a slow release fertiliser on establishment and early growth;
2. vegetation establishment on angle of repose and 1:3 batter slopes in order to:
   - examine the potential problems of ecosystem establishment on steep slopes; and
   - determine the longer-term effects on slope stabilisation;
3. initial nutritional treatments on establishment and early growth of four *Eucalyptus* species (fertiliser rates, ectomycorrhizal inoculation);
4. effect of seed imbibition and mulching on germination, survival rates and early growth of four *Eucalyptus* species;
5. effect of mulch type on seed germination and early growth of a range of eucalypt and other native species; and
6. effects of eucalypt seed application rates.

Monitoring was carried out about 12 weeks after establishment (Reddell & Spain 1995) and again two years (Gordon et al 1995) and five years (Gordon et al 1997) later.

Two key findings of this series of experimental trials were described by Reddell & Spain (1995), namely:

- the extremely low survival of eucalypt seed sown into minesoils on the waste rock stockpiles if no surface amelioration treatments were used. Although seed was of good viability, an average of less than 0.5% of the viable seed germinated and survived the 12 week period immediately after sowing. Extreme fluctuations in surface micro-climatic conditions (especially temperature and moisture) were likely to be responsible for the high seed mortality; and
- identification of mulching as a possible approach to alleviate this problem and increase seed survival and establishment rates. Mulch type was critical. A thin layer of eucalypt mulch was by far the most effective treatment, increasingly seedling survival rates for some species by up to 40 times.

Thus, two distinct stages of seedling establishment were recognised, each of which may require different management practices and inputs. The first of these stages is seed survival, germination and early establishment. Seed and seedlings in this stage appear very susceptible to surface conditions on waste rock stockpiles and ameliorative treatments are required for effective seed establishment. The second stage involves subsequent seedling growth and plant community development. Mycorrhizal inoculation and limited fertiliser application are likely to be required to maximise seedling survival and optimise seedling growth rates during this later stage.

The trials focussing on nutritional treatments were the subject of special investigation (Reddell et al 2000). Spores of 11 species of fungi had been used in this experiment because all were successful in initiating ectomycorrhizas with *Eucalyptus miniata* seedlings in the glasshouse. However, many of these associations did no persist after 29 weeks from planting out in the field. Two fungal species (*Pisolithus* and *Laccaria*) showed a significantly greater ability to persist compared to four other fungal treatments. Cross-contamination of inoculant fungi between different treatment plots was rare. However, there was a high incidence of a local 'contaminant' ectomycorrhizal fungus on root systems of some seedlings where the inoculant fungus had not persisted.

Average rates of seedling survival in the field were high (between 95 – 100%) and were unaffected by the occurrence of different ectomycorhhizas on the root systems. Shoot growth and leaf phosphorus contents did differ significantly with different ectomycorrhizal associations. Highest dry weights and leaf phosphorus concentrations were found in seedlings with ectomycorrhizas formed by the inoculant and local 'contaminant' fungi.

The results clearly demonstrate that the re-introduction of specific ectomycorrhizal fungi into minesoils on waste rock stockpiles enhances the establishment, growth and nutrition of *E. miniata* seedlings. This more rapid early establishment and growth performance should lead to more effective competition with grasses and other colonising species. Gordon et al (1997) pointed out that this is one mechanism for accelerating the development of more predictable, eucalypt-dominated native woodland ecosystems on waste rock landforms.

5.6.11 Large scale revegetation trials

Large scale revegetation trials (Cramb et al 1998) were undertaken on the low grade ore and waste rock stockpiles to compare the effectiveness and operational feasibility of a range of methods for establishing self-sustaining native woodland ecosystems. The trials were based on earlier findings that:

- vegetation can be established directly into the incipient soils ('minesoils') forming in waste rock without the requirement for topsoil; and
- 'successional' development of rehabilitation with acacias and grasses was not predictable and would not, in the short term, lead to the development of the desired eucalypt-dominated forest and woodland communities.

Various vegetation techniques were trialed including planting tubestock, direct seeding and spreading 'woody' root material with potential for vegetative regeneration. Of the three establishment methods, planting tubestock gave the highest rate of success but was the most labour intensive and costly.

A number of large scale trials were designed by CSIRO (Reddell & Hopkins 1995) to investigate:

1. the effects of a surface wood mulch and of supplying RP2 irrigation water on early establishment (germination and survival) from seed;
2. the interactive effects of surface mulch, fertiliser, mycorrhizal inoculation and irrigation on survival and growth;
3. the effect of a non-aggressive grass species on community development under two irrigation regimes;
4. the effects of different proportions of acacia in the seed mix on plant community development;
5. the interactive effects of seeding rate and seed mix diversity on community development under a single irrigation regime;
6. the effects of species diversity and planting density on growth and subsequent community development without irrigation; and
7. the survival and establishment of monsoon vine forest species on the stockpiles with that of sclerophyll woodland species.

Of the seven experiments, the latter five were of a longer term nature and initial monitoring did not provide meaningful results.

In experiment 1, initial monitoring indicated that water availability was clearly important in germination, early establishment and growth of seedlings from seed. There was an average of 53 seedlings per plot in the irrigated plots compared with 1 seedling per plot for non-irrigated plots. Whilst mulch rate did not have a significant effect on the early establishment and growth of seedlings from seed, there were approximately 50% more seedlings at the higher mulch rate than at the lower mulch rates.

In experiment 2, no effects of the interaction between fertiliser, mycorrhizal inoculation of seed and mulch on seedling growth were found.

Because of funding limitations, the experiments were not assessed after the initial monitoring.

5.6.12 Monitoring the effectiveness of the revegetation trials – Landscape Function Analysis

Many of the revegetation trials on the waste rock stockpiles have been assessed in terms of landscape, vegetation and 'soil' indicators by CSIRO (Ludwig et al 1997b, Ludwig et al 1997a). In terms of soil surface attributes, soil surface condition class (SSCC) varied significantly on sites of different ages, with the oldest site examined (12.5 years) having the greatest nutrient index value (68%). Older sites had substantial leaf litter and grasses that protected the soil surface from rain-splash erosion and contributed to nutrient cycling. In terms of vegetation attributes, all but one site (vegetated in 1988 with some use of topsoil) had a high proportion of eucalypts. However, Ludwig et al (1997b) noted that the practice of using topsoil on rehabilitated sites promoted the growth of annual grasses and weeds. This provides large quantities of fuel for fires which kills establishing trees before they reach a fire resistant age. In addition, although acacias (eg *Acacia holosericia*) are also killed, they regenerate from seeds quickly after a fire, making the site again prone to fire. Thus the vegetation becomes trapped into an *Acacia*/*Sorghum* fire cycle that is a well known problem on minesites in northern Australia.

On older sites where tree heights were generally above 1.5m, good tree growth was indicated by relatively high mean diameter at breast height (DBH). Ludwig et al (1997b) noted that these mean DBH values were about as high as that found for a nearby natural savanna site.

Ludwig et al (1997b) suggested that, based on the LFA data, the current strategies of planting directly into minesoils without the use of topsoil are appropriate for rehabilitating waste rock stockpiles, and that the vegetation is likely to develop into savannas similar to those in the surrounding region. They commented on the practice of deep-ripping of the surfaces prior to planting, in the sense that the resulting troughs progressively accumulate leaf litter to initiate nutrient cycling and soil forming processes. Planting of *Eucalyptus*-rich species assemblages promotes rapid litter production. These processes, in turn, stimulate tree growth and the establishment of new tree, shrub and perennial grass seedlings. All these landscape and biological processes indicate that the sites have a high probability of developing into self-sustaining savanna ecosystems.

5.6.13 Corbett review of revegetation and ERA critique

The Corbett review (Corbett MH 1999) was commissioned by the OSS as part of its watching brief on revegetation research and aimed to assist ARRTC in determining whether current practices and plans for revegetation at Ranger mine and elsewhere in the ARR were appropriate, and to establish research priorities in the region. The majority of the information regarding revegetation in the wet-dry tropics of northern Australia pertains to Ranger mine. However, Corbett found that there was a dearth of peer-reviewed published papers which he suggested were a significant problem that may limit effective communication and application of appropriate revegetation techniques on mines in the region.

Corbett went on to state that the use of topsoil on hard rock mines in northern Australia was a contentious issue, with topsoil respreading being excluded from many revegetation programs. He suggested that the experience of many rehabilitation researchers in the wet-dry tropics indicated that the use of topsoil containing indigenous microbes, valuable nutrients and organic matter increases the probability of achieving a successful, self-sustaining native ecosystem in the long term. Because of the negative effects associated with stored topsoil use at hard rock mines, Corbett suggested that researchj was required on effective collection, handling and storage strategies for stored topsoil. Studies werev also needed to determine the minimum amount of topsoil required for effective rehabilitation.

A paucity of literature on the long-term successional development of revegetated areas in the wet-dry tropics was noted. On disturbed sites, the dominance by early successional species such as acacias had been found to retard successional development, with poor recruitment of eucalypts and other species to these systems, according to Corbett. Given the discrapancy between the time scales of many revegetation programs and subsequent lease relinquishment, and the time required to effect succession, accurate prediction of successional development of young rehabilitated areas is important. Corbett suggested that research was also required to produce a body of organised, reliable theory and practice for industry on the selection, germination and establishment of a composite of species that will increase the likelihood of successional development toward a target ecosystem.

Corbett suggested that perhaps the most important issue affecting the successional development of young rehabilitated areas towards self-sustaining native vgetation communities was fire. The existing literature pertaining to the role of fire in tropical systems focuses on mature systems rather than on young rehabilitated areas. He recommended that research was needed to establish the time required for the development of fire resistance in the various woody components of rehabilitated areas. These was also a need to quantify the frequency and timing of burning regimes that could reduce the risk of high intensity fire in younger rehabilitation and direct species composition/successional development of older rehabilitation.

Corbett then went on to state that there was a requirement, both during and upon completion of rehabilitation, for the dveloped landform, soils and vegetation to monitoring and assessments made of how successful the rehabilitation process has been. His review examined five methodologies that had been used to assess the success of rehabilitation in the wet-dry tropics. He also identied gaps in the existing knowledge or practices that might limit the success of revegetation at minesites in the ARR. The most critical of these were considered to be broadly: topsoil utilisation and management; fire; management/prediction of successional processes; establishment of symbiotic microorganisms; native seed collection, storage and germination; development of monitoring methodologies and acceptable success criteria; and technology transfer.

In its response to ARRTC on the findings of the Corbett review, ERA provided the following critique.

The Corbett MH (1999) review of revegetation of mined land in the wet-dry tropics of northern Australia for the Alligator Rivers Region Technical Committee provides a useful broad overview of practices and plans gleaned from unpublished reports and the scientific literature. However, the strategies he promotes involving the use of topsoil and the concept of succession have arisen from a traditional 'agricultural' approach to revegetation and ecosystem reconstruction. Although still promulgated widely in the context of minesite rehabilitation, these strategies were rejected early in the development of revegetation strategies at Ranger in place of a specific scientific approach to accelerating ecosystem reconstruction on constructed landforms and in disturbed landscapes. The Ranger strategy has been to plant (or seed) framework woodland species directly into 'minesoils', without using natural topsoil materials or 'successional' development. In fact, there is no evidence from studies of native forest dynamics in the monsoonal tropics that a successional sequence occurs. However, the use of topsoil, and some adaptations of successional development, do have value at some minesites and this has been demonstrated at bauxite mines such as at Weipa (Reddell & Hopkins 1994) and Gove (Reddell et al 1993).

There has been a number of assessments of the progress and success (or otherwise) of the Ranger revegetation strategies from the perspective of vegetation attributes, Landscape Function Analysis (landscape, vegetation and soil attributes) and colonisation by native vertebrate and invertebrate species (whole ecosystem monitoring). The assessments have indicated that the revegetation strategies developed at Ranger have a high probability of developing into self-sustaining savanna ecosystems that match natural analogues in the surrounding landscapes.

A recent review by CSIRO ratifies the approach taken and provides the basis for ERA to continue to refine its revegetation strategy in preparation for progressive rehabilitation of the final landform. Concurrently, R&D investigations by EWL Sciences are preparing designs for the final landform (Milnes et al 2001) and setting targets for reconstructed ecosystem attributes (Hollingsworth et al 2001).

5.6.14 Revegetation issues at Nabarlek

Revegetation at Nabarlek has been extensively discussed recently, principally because of a lack of agreement among stakeholders as to the desired outcome (Klessa 2001b). This was illustrated by a lack of agreement within the Nabarlek Decommissioning Working Group on revegetation standards (McGill & Fox 2001). Nevertheless, in December 1993, Queensland Mines Ltd, the mining company, agreed with the Northern Lands Council in a Settlement Deed that the primary objective of the revegetation program was to return mined areas 'to a self sustaining woodland community that blends in with the surrounding environment' (Prendergast et al 1999). In an attempt to resolve the situation, Queensland Mines Ltd appointed Dr M Adams of Adams Ecological Services to act as an independent expert to determine whether satisfactory revegetation of the mine site had occurred. This resulted in a report on the status of the revegetation being compiled (Adams Ecological Consultants 1999). The report was reviewed by Prendergast et al (1999) who disagreed with many of the findings and concluded that:

- Further revegetation work was required if succession to a woodland community was to be achieved,
- Grasses and weeds dominated ground cover on up to 50% of the mine site,
- Appropriate indicators of revegetation success needed to be identified
- Remedial action at a number of sites was required because of excessive erosion,
- The conclusions in the report were not supported by the data presented and, as a result, the report should be revised, and
- An active management plan was needed to address issues such as fire management, weed eradication, feral animal eradication, erosion control and contaminant transport.

A workshop to consider these two reports and to identify further actions, including research was held in April 2000 (Klessa 2001b). About 40 relevant stakeholders (the mine owner and its consultant declined their invitations) considered the following questions:

1. Has rehabilitation reached a stage where the mining company can be discharged of its responsibility?
2. If not, has adequate monitoring data been collected that will allow the success of rehabilitation to be measured?
3. What are the lessons learnt that can be applied now, or further research that should be done?

The outcomes clearly stated that the company should not be discharged of its responsibility and that further monitoring was required (Klessa 2001b). Specific issues to consider further included: bush tucker plants should not be planted on site; preventative fire management should be implemented for revegetated areas for at least the first 5 years; fire breaks should be maintained; a weed control strategy should be developed; and feral animals should be excluded from the site. In support of specific research needed to address these issues, the

Supervising Scientist agreed to financially support an Australian Centre for Mining Environmental Research on Ecosystem Function Analysis (EFA) at Nabarlek. The main tasks of EFA are the determination of ecosystem development trajectories to assess rehabiliatation progress. These are related to species composition and growth rates of vascular plants and the development of ecological niches for fauna (Tongway 2001). A report on this work is expected in December 2002.

6 Key Knowledge Needs

6.1 Development of Key Knowledge Needs

Following consideration of the material presented in an earlier version of this report. The Alligator Rivers Region Technical Committee (ARRTC) developed a framework to allow knowledge gaps to be filled. This framework became known as the *Key Knowledge Needs*.

The objective of the Key Knowledge Needs is:

> *To undertake relevant research that will generate knowledge leading to improved management and protection of the Alligator Rivers Region and monitoring that will be sufficiently sensitive to assess whether or not the environment is protected to the high standard demanded by the Australian government and community.*

In assessing the *Key Knowledge Needs* for research and monitoring in the Alligator Rivers Region, ARRTC has taken into account current mining plans in the region and the standards for environmental protection and rehabilitation determined by the Australian Government.

The assumptions made for uranium mining operations in the region are:

- Mining of uranium at Ranger is expected to cease in about 2008. This will be followed by milling until about 2011 and final rehabilitation expected to be completed by about 2016;

- Nabarlek is decommissioned but has not reached a status where the NT Government will agree to issue a Revegetation Certificate to the mine operator. Assessment of the success of rehabilitation at Nabarlek is ongoing and is being used as an analogue for rehabilitation at Ranger;

- Jabiluka will remain in a care and maintenance condition for some years, at least until mining ceases at Ranger; and

- It is unlikely that any proposal will be brought forward for mining at Koongarra in the foreseeable future.

This scenario is considered to be a reasonable basis on which to base plans for research and monitoring, but such plans may need to be amended if mining plans change in the future. ARRTC will develop a series of possible future scenarios regarding uranium mining in the ARR, and will ensure the research and monitoring strategy is flexible enough to accommodate any new knowledge needs.

The Commonwealth Government has specified Primary and Secondary environmental objectives for mining at Ranger in the Ranger Environmental Requirements. Similar standards would be expected for any future mining development at Jabiluka or Koongarra.

Specifically, under the Ranger Environmental Requirements (ERs):

> *The company must ensure that operations at Ranger are undertaken in such a way as to be consistent with the following primary environmental objectives:*
>
> *(a) maintain the attributes for which Kakadu National Park was inscribed on the World Heritage list;*

(b) maintain the ecosystem health of the wetlands listed under the Ramsar Convention on Wetlands (i.e. the wetlands within Stages I and II of Kakadu National Park);

(c) protect the health of Aboriginals and other members of the regional community; and

(d) maintain the natural biological diversity of aquatic and terrestrial ecosystems of the Alligator Rivers Region, including ecological processes.

With respect to rehabilitation at Ranger, the ERs state that:

The company must rehabilitate the Ranger Project Area to establish an environment similar to the adjacent areas of Kakadu National Park such that, in the opinion of the Minister with the advice of the Supervising Scientist, the rehabilitated area could be incorporated into the Kakadu National Park.

The ERs go on to specify the major objectives of rehabilitation at Ranger as follows:

(a) revegetation of the disturbed sites of the Ranger Project Area using local native plant species similar in density and abundance to those existing in adjacent areas of Kakadu National Park, 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) stable radiological conditions on areas impacted by mining so that, the health risk to members of the public, including traditional owners, is as low as reasonably achievable; members of the public do not receive a radiation dose which exceeds applicable limits recommended by the most recently published and relevant Australian standards, codes of practice, and guidelines; and there is a minimum of restrictions on the use of the area;

(c) erosion characteristics which, as far as can reasonably be achieved, do not vary significantly from those of comparable landforms in surrounding undisturbed areas.

While there are many possible different structures that could be used to specify the Key Knowledge needs, ARRTC has chosen to list the knowledge needs under the following headings:

- Ranger – current operations;
- Ranger – rehabilitation;
- Jabiluka;
- Nabarlek;
- General Alligator Rivers Region; and
- Knowledge management and communication.

6.2 Key Knowledge Needs

1 Ranger – current operations

ARRTC believes that the knowledge (research) needs relating to the current management of the uranium mining operations in the ARR would be best organised within a risk management framework. Such a framework would permit the various risks to the ARR to be assessed using a consistent, quantitative methodology and to be placed in priority order. Risk management is built on the use of quantitative predictive models to link threats or stressors with potential adverse ecological effects.

ERISS is undertaking some ecological risk assessment work, but we believe this needs to be upgraded and made the central focus of the research program. Proposals for research should then be assessed in terms of how the knowledge generated will contribute to the management of risk from the mining operations.

1.1 Reassess existing threats

1.1.1 Surface water transport of radionuclides: Using existing data, assess the present and future risks of health problems to the aboriginal population eating bush tucker potentially contaminated by the mining operations bearing in mind that the current traditional owners derive a significant proportion of their food from bush tucker.

1.1.2 Atmospheric transport of radionuclides: Using existing data and atmospheric transport models, review and summarise, within a risk framework, doses for members of the general public arising from operations at the Ranger mine.

1.2 Ongoing operational issues

1.2.1 Ecological risks via the surface water pathway: In order to place the off-site contaminant issues at Ranger in a risk management context, a conceptual model of transport/exposure/effects pathways should be developed. This process should include a review and assessment of the existing information on the risks of the bioaccumulation and trophic transfer (i.e. biomagnification) of uranium and other Ranger mining-related contaminants from all exposure pathways and including the identification of key information gaps.

1.2.2 Land irrigation: Investigations are required on shallow groundwaters in the land irrigation areas adjacent to Magela Creek as a diffuse source of contaminants. Contaminants of interest/concern in addition to radionuclides are magnesium, sulfate and manganese. Further, the status of the irrigation areas in relation to decommissioning requirements (including radiological risk) needs to be assessed. Water quality models will be linked to knowledge of ecological effects.

1.2.3 Wetland filters: The key research issue associated with wetland filters in relation to ongoing operations is to determine whether their capacity to remove metals (principally uranium) from the water column will continue to meet the needs of the water management system in order to ensure protection of the downstream environment. Related to this is a reconciliation of the solute mass balance particularly for the Corridor Creek System.

1.2.4 Ecotoxicology: Although a great deal of ecotoxicological research and assessment has been undertaken, there are still a number of key issues that remain to be addressed including uranium toxicity measurements for two additional local native species, completion of research on the toxicity of magnesium including the ameliorative effects of calcium, and an assessment of the toxicity of manganese. Other issues that should be considered could include the relationship between dissolved organic matter and uranium toxicity and the effects of suspended sediment on aquatic biota.

1.2.5 Assurance program for radionuclide surface water transport: Further research on surface water dispersion of radionuclides is not considered necessary on the basis of risk. However, a continuing program of monitoring of radionuclides in surface water and in aquatic biota is considered necessary to provide assurance for aboriginal people who source food items from the Magela creek system downstream of Ranger.

1.2.6 Radiation exposure of workers: Further work should be considered in three areas: (a) a more robust examination of radon loss from dust particles, (b) development of a system which measures the concentration of radioactive dust and radon progeny in the breathing zone of a worker whilst wearing respiratory protection, and (c) measurement of the AMAD and solubility of ore and product dusts in a range of exposure scenarios.

1.3 Monitoring

1.3.1 Surface water, groundwater, chemical, biological, sediment, radiological monitoring: Routine and project-based chemical, biological, radiological and sediment monitoring should continue. There is very little research required for the continued implementation of these programs although there is scope for some specific research and analysis in relation to the review of the occupational radiological monitoring program. More specifically, ARRTC supports the design and implementation of a new risk-based radiological monitoring program based on a robust statistical analysis of the data collected over the life of Ranger.

2 Ranger – rehabilitation

Mining and milling at Ranger is likely to cease by about 2011. Closure of the Ranger mine requires a large number of decisions, many of which will be dependent upon high quality scientific and technical information. The generation of this information will be the major focus of Ranger over the next five years. It will also be necessary to develop a holistic monitoring strategy, based on the risk assessments (and the associated models) recommended above, that aims to quantify changes in the identified high risk areas or test outcomes predicted by the models.

2.1 Landform design

2.1.1 Development and agreement of closure criteria from the landform perspective: Closure criteria from the landform perspective need to be established at both the broad scale and the specific. At the broad scale, agreement is needed, particularly with the traditional owners and within the context of the objectives for rehabilitation incorporated within the ERs, on the general strategy to be adopted in constructing the final landform. These considerations would include issues such as maximum height of the landform, the maximum slope gradient (from the aesthetic perspective), and the presence or absence of lakes or open water. At the specific scale, some criteria could usefully be developed as guidance for the initial landform design such as slope length and angle (from the erosion perspective), the minimum cover required over low grade ore, and the minimum distance of low grade ore from batter slopes. Specific criteria are needed that will be used to assess the success of landform construction. These would include, for example, maximum radon exhalation and gamma dose rates, maximum sediment delivery rates, maximum constituent concentration rates in runoff and maximum settling rates over tailings repositories.

2.1.2 Initial landform design: An initial design is required for the proposed final landform. This would be based upon the optimum mine plan from the operational point of view and it would take into account the broad closure criteria, engineering considerations and the specific criteria developed for guidance in the design of the landform. This initial landform would need to be optimised using the information obtained in detailed water quality, geomorphic, hydrological and radiological programs listed below.

2.1.3 Water quality in seepage and runoff from the final landform: Existing water quality monitoring and research data on surface runoff and subsurface flow need to be analysed to develop models for the quality of water, and its time dependence, that would enter major drainage lines from the initial landform design. Options for adjusting the design to minimise solute concentrations and loads leaving the landform need to be assessed.

2.1.4 Groundwater modelling: In addition to the seepage and runoff issues discussed above, there is a specific need to address the existence of mounds under the tailings dam and waste rock stockpiles. Models are needed to predict the behaviour of groundwater and solute transport in the vicinity of these mounds and options developed for their remediation to ensure that on-site revegetation can be achieved and that off-site solute transport from the mounds will meet environmental protection objectives.

2.1.5 Geomorphic and geochemical behaviour and evolution of the landform: The existing data set used in determination of the key parameters for geomorphological modelling of the proposed final landform should be reviewed after consideration of the near-surface characteristics of the initial proposed landform. Further measurements of erosion characteristics should be carried out if considered necessary. The current site-specific landform evolution models should be applied to the initial proposed landform to develop predictions for long term erosion rates, incision and gullying rates, and sediment delivery rates to the surrounding catchments. Options for adjusting the design to minimise erosion of the landform need to be assessed. In addition, an assessment is needed of the geomorphic stability of the Ranger minesite with respect to the erosional effects of extreme events.

2.1.6 Radiological characteristics of the final landform: The characteristics of the final landform from the radiological exposure perspective need to be determined and methods need to be developed to minimise radiation exposure to ensure that restrictions on access to the land are minimised. Radon emanation rates, gamma dose rates and radionuclide concentrations in dust need to be determined and models developed for both near-field and far-field exposure. The pre-mining radiological conditions should also be reviewed so that estimates can be made of the likely change in exposure rates compared to pre-mining conditions.

2.1.7 Testing of 'trial' landforms: Current landforms at Ranger and at other sites such as Nabarlek should be used to test the various models and predictions for water quality, geomorphic behaviour and radiological characteristics at Ranger.

2.1.8 Final landform design: The detailed design for the final landform at Ranger should be determined taking into account the results of the above research programs on surface and ground water, geomorphic modelling and radiological characteristics.

2.2 Ecosystem establishment

2.2.1 Development and agreement of closure criteria from ecosystem establishment perspective: Closure criteria for ecosystem establishment need to be established at both the broad scale and the specific. At the broad scale, agreement is needed, particularly with the traditional owners and within the context of the objectives for rehabilitation incorporated within the ERs, on the general strategy to be adopted on habitat types to be incorporated and the species composition of trees, shrubs and grasses to be established on the landform. At the specific scale, criteria are needed that will be used to assess the success of ecosystem establishment. These would include, for example, targets for species density and abundance and measures of faunal return.

2.2.2 Characterisation of terrestrial and aquatic ecosystem types at analogue sites: To implement the revegetation strategy for Ranger Mine, an understanding of the relationships between vegetation communities and key geomorphic features (parent material, slope, effective soil depth, internal drainage characteristics) in surrounding areas of Kakadu National

Park is essential in identifying sustainable and achievable 'landscape' analogues (or target habitats) for the final, post-mine landform at Ranger. Identification and description of these landscape analogues is also the first step in developing robust, measurable, ecologically-based criteria for assessing revegetation performance, function and success.

2.2.3 Establishment and sustainability of ecosystems on mine landform: Research on how the landform, vegetation, fauna habitat, hydrology and geochemistry will be reconstructed at Ranger is essential. *Noting that there are no good examples in the wet-dry tropics of successful reclamation of hard rock mines, priority needs to be given to this research.* Research sites should be established that demonstrate an ability to reconstruct an ecosystem, even if this is at a relatively small scale. Issues that need to be addressed include species selection, seed collection germination and storage, propagation of recalcitrant species, nursery production of seedlings, fertiliser strategies including application methods and direct seeding techniques. Other issues requiring investigation include the return of fauna habitat, potential plant toxicity problems from waste rock, the control and exclusion of weeds and the effects of fire, hydrology and erosion on the rehabilitation strategy.

2.2.4 Radiation exposure pathways associated with ecosystem re-establishment: Bioaccumulation studies conducted to date have focussed on aquatic animal and plant species because of their importance of the aquatic transport pathway, particularly during the operational phase of uranium mining operations. Information on radionuclide uptake by terrestrial animals and plants is required to enable a radiological risk assessment to be carried out for the revegetation program. This needs to be coupled with estimates of terrestrial bushfood consumption by local Aboriginal people. Another radiological issue that requires assessment is the potential for tree roots to penetrate any radon barriers that form part of the rehabilitated landscape.

2.3 Groundwater dispersion

2.3.1 Containment of tailings and other mine wastes: The primary method for protection of the environment from dispersion of contaminants from tailings and other wastes will be containment. For this purpose, investigations are required on the hydrogeological integrity of the pits, the long-term geotechnical properties of tailings and waste rock fill in mine voids, tailings deposition methods, geochemical and geotechnical assessment of potential barrier materials, and strategies and technologies to access and 'seal' the surface of the tailings mass, drain and dispose of tailings porewater, backfill and cap the remaining pit void.

2.3.2 Geochemical characterization of source terms: Investigations are needed to characterise the source term for transport of contaminants from the tailings mass in groundwater. These will include determination of the permeability of the tailings and its variation through the tailings mass, strategies and technologies to enhance settled density and accelerate consolidation of tailings, and pore water concentrations of key constituents. Assessment is also needed of the effectiveness (cost and environmental significance) of paste and cementation technologies for increasing tailings density and reducing the solubility of chemical constituents in tailings.

2.3.3 Aquifer characterization and whole-of-site model: The aquifers surrounding the tailings repositories (Pits 1 and 3) need to be characterised to enable modelling of the dispersion of contaminants from the repositories. This will involve geophysics surveys, geotechnical drilling and groundwater monitoring and investigations on the interactions between the deep and shallow aquifers.

2.3.4 Hydrological/hydrogeochemical modelling: Predictive hydrological/hydrogeological models need to be developed, tested and applied to assess the dispersion of contaminants from the tailings repositories over a period of 10,000 years. These models will be used to assess whether all relevant and appropriate factors have been considered in designing and constructing an in-pit tailings containment system that will prevent environmental detriment in the long term.

2.4 Water treatment

2.4.1 Active treatment technologies for specific mine waters: Substantial volumes of process water retained at Ranger in the tailings dam and Pit 1 must be disposed of by a combination of water treatment and evaporation during the mining and milling phases of the operation and during the rehabilitation phase. Research priorities include developing new treatment technologies and enhanced evaporation technologies that can be implemented for very high salinity process water.

2.4.2 Passive treatment of waters from the rehabilitated landform: Sentinel wetlands may form part of the final landform at Ranger. Research on wetland filters during the operational phase of mining will provide information relevant to this issue. However, there is a need to assess the long-term behaviour of physical and biotic components of wetlands and the ecological health of wetlands which are used to treat runoff from the proposed rehabilitated landform.

2.5 Monitoring

A monitoring program to assess the success of rehabilitation at Ranger will be essential. Prior to its design and implementation, clear and agreed closure criteria will be needed as indicated above. These criteria should be used to determine the design of the monitoring program.

2.5.1 Monitoring of the rehabilitated landform: A new management and monitoring regime for the rehabilitated Ranger landform needs to be developed and implemented. It needs to address all relevant aspects of the rehabilitated landform including ground and surface water quality, radiological issues, erosion, flora, fauna, weeds, and fire.

2.5.2 Off-site monitoring during and following rehabilitation: A monitoring regime for the downstream environment is also required to assess rehabilitation success with respect to protection of the downstream environment. This program should address the dispersion of contaminants by surface water, ground water and via the atmosphere.

3 Jabiluka

The Jabiluka project has now entered a long-term care and maintenance phase. It is ARRTC's view that ongoing monitoring will be required throughout this period. In addition, a review is needed of knowledge that would be required prior to any proposal to develop Jabiluka. In particular, it will be necessary to identify and implement any projects considered essential in providing this knowledge well in advance of any development plans.

3.1 Monitoring

3.1.1 Monitoring during the care & maintenance phase: The monitoring regime for Jabiluka during the care and maintenance phase needs to be determined, implemented and regularly reviewed. The monitoring program (addressing chemical, biological, sediment and radiological issues) should be commensurate with the environmental risks posed by the site, but should also serve as a component of any program to collect baseline data required before development such as meteorological and sedimentary data.

3.2 Research

3.2.1 Research required prior to any development: A review of knowledge needs is required to assess minimum requirements in advance of any development. This review would include the groundwater regime (permeabilities, aquifer connectivity etc), hydrometeorological data, waste rock erosion, assess site-specific ecotoxicology for uranium, additional baseline for flora and fauna surveys.

4 Nabarlek

Nabarlek is decommissioned but has not reached a status where the NT Government will agree to issue a Revegetation Certificate to the mine operator. Since Nabarlek is the first Australian uranium mine of the modern era to complete operations and be rehabilitated, ARRTC believes that Australia needs to ensure that an overall assessment of the success of rehabilitation at Nabarlek is carried out. The Nabarlek site should also be used as an analogue for rehabilitation at Ranger and projects at Nabarlek should be designed to address specific issues of concern at Ranger.

4.1 Success of revegetation

4.1.1 Revegetation assessment: The principal ongoing issue at Nabarlek is the poor revegetation. Assessment of the adequacy of revegetation at the site should continue and, following its completion, management options should be developed and submitted to the mine-site technical committee for its consideration.

4.1.2 Development of revegetation monitoring method: A methodology and monitoring regime for the assessment of revegetation success at Nabarlek needs to be developed and implemented. Currently, resource intensive detailed vegetation and soil characterisation assessments along transects located randomly within characteristic areas of the rehabilitated landform are being undertaken. Whilst statistically valid, these assessments cover only a very small proportion of the site. Remote sensing (satellite) data are also being collected and the efficacy of remote sensing techniques for vegetation assessment should continue. The outcomes of this research will be very relevant to Ranger.

4.2 Assessment of radiological, chemical and geomorphic success of rehabilitation

4.2.1 Overall assessment of rehabilitation success at Nabarlek: The current program on erosion, surface water chemistry, groundwater chemistry and radiological issues should be continued to the extent required to carry out an overall assessment of the success of rehabilitation at Nabarlek. In particular, all radiological exposure pathways should be evaluated and a comprehensive radiation dose model for Nabarlek should be developed.

5 General ARR

5.1 Landscape scale analysis of impact

Apart from regular refinement of procedures for the current monitoring programs, a potential major future research area is the possible development of broader, landscape scale programs that would enable possible effects of mining to be distinguished from those arising from other causes. Such a program was recommended by the Independent Science Panel of the World Heritage Committee. Initial studies have been undertaken. However, ARRTC believes that, before committing further resources to this program, a review of the program to assist in determining future priorities needs to be undertaken.

5.1.1 Re-assess and prioritise the landscape program: A review is required, within a conceptual modelling and risk assessment framework, of the landscape wide program to determine options and priorities for the future development of this program.

5.2 South Alligator River valley rehabilitation

The focus of work to develop and implement a rehabilitation strategy for historic uranium mining related sites in the South Alligator Valley is the identification of a suitable site for the burial of radiologically active mining residues such as uranium ores or sediments contaminated with tailings. Parks Australia is responsible for this program. Once potential sites have been identified based upon hydrology, access, stability, cultural and other considerations, groundwater investigations will be required to ensure that the site meets requirements for minimum separation between the base of the repository and top of the water table.

5.2.1 Assessment of mine sites in the South Alligator River valley: SSD conducts regular assessments of the status of mine sites in the SAR valley, provides advice to Parks Australia on technical issues associated with its rehabilitation program and occasionally conducts a low level radiological monitoring program, primarily for assurance purposes. ARRTC believes these should continue.

5.3 Develop monitoring program related to West Arnhem Land exploration activities

Mineral exploration is proceeding in the eastern area of the ARR in Arnhem Land outside the Kakadu National Park. In order to overcome the common problem of inadequate baseline data for correctly identifying the cause of environmental change, the SSD and NLC have jointly advocated the strategic collection of regional baseline information on aquatic ecosystems in areas adjacent to mineral exploration sites in the ARR.

5.3.1 Baseline studies for biological assessment in West Arnhem Land: In areas adjacent to mining exploration sites, ARRTC believes there is a need to determine a baseline for (a) rare, threatened and endemic biota and (b) indicator species or groups such as macroinvertebrates.

5.4 Koongarra

There are currently no plans for the development of the Koongarra uranium prospect. However, it is ARRTC's view that, subject to the prioritisation of available resources, an ongoing base-line data collection program could be established and the value of Koongarra as an analogue for pre-mining radiological conditions at Ranger could be investigated.

5.4.1 Baseline monitoring program for Koongarra. A low level monitoring program should be developed for Koongarra to provide baseline data in advance of any possible future development at the site. Data from this program may also have some relevance as a control system for comparison to Ranger, Jabiluka and Nabarlek.

5.4.2 Analogue information for pre-mining conditions at Ranger: The value of Koongarra as an analogue site for pre-mining radiological conditions at Ranger should be investigated. There are some pre-mining radiological data for Ranger but the value of these data could be greatly enhanced if it could be extrapolated, through the use of an undisturbed analogue site such as Koongarra, to provide further information on parameters such as pre-mining gamma dose rates, radon exhalation, and radioactivity concentrations in dust.

6 Knowledge management and communication

The ARR is one of the most studied regions in Australia. Consequently, a very large amount of knowledge has been accumulated over the years on this system. The stimulus for the research is that knowledge-based management of the uranium mines is the best approach to ensuring minimal risk to the ARR.

ARRTC believes that additional emphasis needs to be put on knowledge management and exchange in the next five years. Key aspects that will need to be addressed include:

6.1 Integrated framework

6.1.1 Development of an integrated framework: This has already commenced within a landscape analysis framework and is linked with the development of conceptual models of the ARR recommended above. Such an integrated framework will assist with the communication of the various risks to the system and its people from the uranium mines.

6.2 Uncertainty analysis

6.2.1 Uncertainty analysis of data and communication: People involved in the management of natural resources rarely have all the information they need. Even in the ARR, where a very large amount of research has been undertaken on the possible impacts of uranium mining, there is still much not known about the risks. ARRTC believes that management of the mining operations would be improved if the uncertainties in the risk assessment were explicitly identified and communicated. Additionally, those higher risk areas where the uncertainty is greater would be targeted for more research. It is expected that current work on the development of conceptual models of the ARR will clarify many of these uncertainties.

6.3 Effective communication channels between research providers

6.3.1 Establishing effective communication channels between and within research providers: There are a large number of organisations undertaking research in the ARR including SSD, EWLS, ERA, Parks Australia North and CSIRO. Given limited resources, it is critical that research is not being duplicated or previous studies repeated. ARRTC believes that communication between the various research providers could be improved and become more formalised to ensure better outcomes for all parties.

6.4 Effective communication to stakeholders

6.4.1 Effective communication of science to stakeholders: There are a large number of stakeholders with direct and indirect interests in uranium mining in the ARR. It is critical that the results of the high quality research being undertaken in the ARR is communicated to all stakeholders in the most relevant format. ARRTC believes that the various research providers need to target their communication strategies more specifically to the various stakeholder groups.

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