Supervising Scientist Monitoring Program

Instigating an environmental monitoring program to protect aquatic ecosystems and humans from possible mining impacts in the Alligator Rivers Region

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May 2002

Contents

1 Background

Through his research programs, the Supervising Scientist has developed biological, chemical and radiological techniques that would be used to monitor and assess impacts upon ecosystems and humans arising from mining activities at Ranger and Jabiluka. In the course of this research work, relevant monitoring data have been gathered spanning a period that for many indicators dates back over a decade. Nevertheless, the 2001–02 Wet season was the first time the Supervising Scientist has *formally* undertaken a full environmental monitoring program. The background to developments in instigating this monitoring program are summarised below.

1.1 Primary impetus for instigating an environmental monitoring program

In response to the tailings water leak at Ranger (in the 1999–2000 Wet season), the Supervising Scientist recommended that his Division develop and implement a routine environmental monitoring program whose focus was on the provision of advice on the extent of protection of the people and ecosystems of Kakadu National Park (Supervising Scientist 2000). This recommendation was picked up and endorsed in the Final Report on Jabiluka of the Independent Science Panel (ISP) of ICSU and the International Union for the Conservation of Nature (IUCN) (ISP & IUCN 2000). The report stated:

> *The ISP would wish the Australian Government to put the new monitoring arrangements [recommended in the Supervising Scientist's report on the tailings water leak at Ranger] for Jabiluka in place without delay …* (Recommendation 8, section 9.3, p 30).

This requirement also complements another ISP recommendation calling for landscape and ecosystem analyses, in combination with a survey and monitoring program. Collectively, these pre-mining data *would enable the effects of mining-related activity to be distinguished from those due to other causes*. (Recommendation 6, section 9.2 (g), p 29).

In response to the Supervising Scientist's tailings water leak report and the ISP/IUCN recommendations on monitoring requirements for Jabiluka, the Government provided the Supervising Scientist with additional resources to implement a routine environmental monitoring program focusing on human and ecosystem protection in Kakadu National Park. A preliminary monitoring program was implemented by the Supervising Scientist during the 2000–01 Wet season, while the finalised program commenced during the 2001–02 Wet season.

The main risk identified for ecosystems surrounding mine sites in the Alligator Rivers Region (ARR, enclosing Kakadu National Park) is from dispersion of mine waste waters to streams and shallow wetlands during the intense and highly seasonal wet seasons. Thus management of water that accumulates over this time at mine sites and assurance that the environment has not been harmed by any water that leaves the mine sites assume critical importance. For this reason, the environmental monitoring programs instigated for ARR mine sites and which are described in the following sections, focus almost entirely on aquatic ecosystems.

An additional emphasis in the ARR environmental monitoring programs is the focus on biological monitoring. This is in recognition that only studies conducted on aquatic organisms can define and assess the overall effect of contaminants on streams. This is not to say that biological approaches should replace chemical standards and monitoring. Rather, in comprehensive water quality assessment programs, both approaches are highly complementary and interdependent.

1.2 Earlier progress at implementing routine ARR monitoring programs

Previous work by ***eriss*** relevant to environmental monitoring in the Alligator Rivers Region focused on the development and transfer of techniques to mining companies. In a briefing paper for the 1997 Alligator Rivers Region Technical Committee (ARRTC) meeting (Humphrey & Pidgeon 1998), progress to 1997 in developing these monitoring programs was described. Key issues raised in the briefing paper were:

- A summary of research leading to development of monitoring techniques, emphasising the ongoing refinement of techniques, and referring to and summarising key outcomes of a Specialist Workshop held in Canberra in 1993 to review ARR monitoring programs (see Finlayson & Humphrey 1998).
- An introduction to the concept of a 'demonstration' program, ie:

  The period of development and refinement of methods for biological monitoring is very near completion. Protocols should be prepared for these techniques as a priority task. It is timely that ***eriss*** *now enters a period of program implementation, in which core elements serve as demonstration projects that would eventually be handed over to Energy Resources of Australia (ERA)* (Humphrey & Pidgeon 1998).

A more detailed description of the elements of the ***eriss*** monitoring program, including the demonstration program, were provided in Humphrey et al (1999). ARRTC members were also updated in 1998 on progress with implementing the demonstration program, including a description of stakeholder consultations that had occurred in preparing the program, and were shown draft protocols for the monitoring techniques.

By 2000, this demonstration program and transfer of techniques had progressed as far as ERA taking up and implementing routinely the technique of creekside monitoring (section 2.2.1.1). Following the 2000–01 Wet season, however, this technology transfer ceased as a consequence of the Government decision for the Supervising Scientist Division to independently conduct off-site monitoring (as described above). Even so, the description of this demonstration program and justification of its elements are as necessary now as when the program was intended for industry's use. These descriptions are provided in sections 2–6 below.

1.3 A template for environmental monitoring and assessment at sites of high conservation value elsewhere

A key recommendation arising from the 1993 external review of the ***eriss*** biological monitoring program (Finlayson & Humphrey 1998) was that the ***eriss*** program be used as a template for situations elsewhere in Australia where such comprehensive monitoring was required. The opportunity to influence national approaches to monitoring in this manner arose in the drafting of the new *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZECC & ARMCANZ 2000a) for which ***eriss*** staff were technical coordinators. The revised Guidelines recognise three ecosystem conditions — highly disturbed, slightly to moderately disturbed, and high conservation value ecosystems — warranting progressively higher standards of protection respectively. Through the revision of the Guidelines, key principles and elements of environmental monitoring and assessment techniques developed by ***eriss*** for the ARR — water physico-chemistry monitoring, toxicity testing and biological monitoring — were also adopted for similar areas of high conservation value in Australia.

In practice, development of the Guidelines and refinement of the ***eriss*** monitoring and assessment techniques occurred in parallel. Input to the Guidelines' revision from external authors, agencies and the public also influenced the approach recommended for water quality guideline derivation, and monitoring and assessment in areas of high conservation value in Australia. As a consequence, the external input also influenced the approach now to be adopted at mine sites in the ARR. The current ARR programs certainly provide a template for others applying the new Guidelines to high conservation areas.

The ***eriss*** biological assessment programs are also being used to develop a conceptual framework for wetland risk assessment (van Dam et al 1999) and monitoring (Finlayson 1996) for the Ramsar Wetland Convention and have influenced approaches being tested by ***eriss*** for vulnerability assessment of wetlands due to climate change and sea level rise (Bayliss et al 1997).

As a consequence of the new, nationally-endorsed framework now available for water quality assessment in Australia (viz ANZECC & ARMCANZ 2000a), it is appropriate to describe management goals, water quality indicators and measurement programs (through design and analysis) for the ***eriss*** environmental assessment programs according to this national approach. These aspects are discussed in the following sections.

2 Rationale and basis for the monitoring program for ecosystems

2.1 Management goals

2.1.1 Tenets of Ecologically Sustainable Development (ESD) applicable to sites of high conservation values

Implicit in the development of the ***eriss*** environmental monitoring programs is the recognition that ecosystems surrounding mine sites in the ARR warrant the highest level of protection. Thus, the Australian Government has accepted that management of ecosystems of high conservation value, such as those in Kakadu, requires adherence to nationally-accepted principles for conserving our natural heritage. These principles are accepted in the Kakadu National Park Plan of Management 1999–2004, and have been developed in consultation with local landholders and other stakeholders.

Management of ecosystems of high conservation value such as those in Kakadu requires adherence to two important Ecologically Sustainable Development (ESD) tenets (ESD Steering Committee 1992): (i) precautionary management, and (ii) conserving and maintaining biological diversity. National and international recognition of this is provided in:

- The revised ANZECC and ARMCANZ (2000a) Water Quality Guidelines;
- The Ramsar obligation to maintain the ecological character of internationally important wetlands and to make wise use of such sites (Davis 1994, Finlayson 1996). This is supported by a Ramsar resolution to undertake ecological risk assessment, incorporating early detection capability (van Dam et al 1999);
- The tenets also conform to the aims of the World Heritage Convention, to encourage nations to protect and conserve natural and cultural heritage of worldwide importance.

In practical terms for such highly-valued sites, this entails establishment of a comprehensive environmental monitoring program, integrating measurements of key chemical and biological indicators collected from key sites (including controls) and times. In meeting the ESD tenets, it would be expected that the monitoring program would have an early detection capability as well as the ability to report on key indicators of biological diversity (ANZECC & ARMCANZ 2000a, van Dam et al 1999). The techniques listed in sections 5 and 6 below accord with these national and international frameworks for monitoring and baseline data collection.

2.1.2 Management goals and hypotheses

As recommended in the new Water Quality Guidelines, management goals and hypotheses associated with assessment of impact at sites of high conservation value should be coached around the objective of *no change to key indicators of biological diversity*[1]. Associated with such a management goal for ecosystems of high conservation value are the following principles (ANZECC & ARMCANZ 2000a):

(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.

(v) Where data for a reference/control site have only been collected for a limited period and the reference condition cannot be clearly characterised, the power of detection should be increased by using more indicators, and/or more reference/control sites and/or more monitoring sites placed along any probable disturbance gradients.

Suitable overarching hypotheses for the monitoring techniques that would support the above-listed principles would include:

1 For physical and chemical indicators:

Where limits have been set on the basis of local biological-effects data (eg uranium in Magela Creek):

- Water quality in receiving waters has not exceeded [1] the limit as a consequence of mining activities.

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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.

In the absence of local biological effects data:

- Water quality in receiving waters has not changed [1] as a consequence of mining activities.

2 For biological early detection indicators:

- Measured biological responses in receiving waters have not changed [1] as a consequence of mining activities.

3 For key indicators of biological diversity (as defined in section 2.2.1.2):

- 'Important'[2] aspects of biological diversity in the receiving waters have not changed [1] as a consequence of mining activities.

2.2 Selection of indicators

2.2.1 Assessment objectives for ecosystem protection

ANZECC and ARMCANZ (2000a) recommend that appropriate indicators and protocols be selected according to the *assessment objectives* that are identified by managers for protection of a water resource. There are three possible assessment objectives:

1. Early detection of short- or longer-term changes;
2. Assessment of biodiversity; and
3. Broad-scale assessment of ecosystem health (at catchment, regional or larger scales);

Assessment objectives 1 and 2 correspond to the ESD tenets of (i) precautionary management, and (ii) conserving and maintaining biological diversity, listed above (section 2.1.1). For sites of high conservation value, the Guidelines recommend that indicators be selected for both of these assessment objectives (1 and 2).

The principles underlying these assessment objectives may be summarised:

2.2.1.1 Early detection of short- or longer-term changes

Precautionary management entails the setting of conservative environmental controls together with responsiveness to changes in early detection indicators measured in a monitoring program. Such management is pre-emptive or preventative in order that large and ecologically important impacts are avoided. Whether the indicators are chemical or biological, the intervention takes place when pre-determined 'triggers' are reached. These triggers are conservative in the sense that, in many cases, the ecological relevance of the measured responses has not been established — if indeed there is any such relevance.

Precautionary management may entail:

Prior to any release of a waste water to the environment, the setting of controls:

- conservative chemical standards; and
- a program of pre-release laboratory toxicity testing, of any waters that are considered for discharge to streams. Discharge rates are determined at which no harm should occur to animals in downstream ecosystems. (Details of the ***eriss*** ecotoxicity program)

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[2] Important changes to biodiversity are defined in section 2.2.1.2.

During or after release, conducting an environmental monitoring program in downstream ecosystems, using (eg):

- creekside monitoring where the responses of organisms exposed to creek waters pumped to creekside shelters are measured during each wet season (see Appendix 2 of this paper for further details of this monitoring technique);
- concentrations of chemicals (including radionuclides) measured in the tissues of long-lived animals (bioavailability/bioaccumulation) at strategic locations downstream to detect far-field effects, including those arising from any potential deposition of mine wastes in sediments; and
- placement of sites in a potential 'disturbance gradient' — such as in a mixing zone, or on the mine site itself, to enhance predictive and early warning capabilities.

2.2.1.2 Assessment of biodiversity

Because changes in 'early detection' indicators may bear no consequence to the integrity of natural populations, communities or ecosystems, there is a need for measurement of suitable surrogates of 'ecosystem-level' and 'biodiversity' change, where important effects might be reflected in (ANZECC & ARMCANZ 2000a):

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

In streams adjacent to mine sites in the ARR, including control streams, monitoring of natural communities of benthic macroinvertebrates and fishes is used to provide information about changes to biological diversity and hence, the ecological importance of any impacts in Magela Creek arising from the mine sites.

2.2.1.3 Broad-scale assessment of ecosystem health (at catchment, regional or larger scales)

The new Water Quality Guidelines recognise that resources will never be adequate to provide detailed, quantitative biological monitoring and assessment of water quality across vast areas of Australia and New Zealand. For such broad-scale assessment, techniques are required to provide quick, cost-effective, first-pass data over large areas. The semi-quantitative data arising from 'rapid biological assessment' may be adequate for management purposes or they may help managers to decide what type of further information may be required and from where.

Up until recently, broad-scale assessment has not been a high-priority requirement in the ARR, where the focus for ***eriss*** has been towards assessment of impact at specific sites in streams downstream of mining impact. However, a level of broad-scale assessment is required to provide:

1. contextual information upon which to assess the ecological importance of impacts;
2. by way of independent spatial controls, an ability to correctly (or more confidently) infer potential mining impact; and most recently
3. a 'landscape' context to assess the natural heritage values of Kakadu, in relation to possible future mining at Jabiluka, as requested by the ISP/IUCN. The broad-scale, 'landscape' approach to environmental assessment requested by the ISP/IUCN will better enable mining-related changes to be distinguished from other changes occurring in the

Region (ie rationale of 2 above) but also enable the natural heritage values themselves to be monitored, as required under World Heritage listing and reporting.

Landscape studies (*sensu* ISP/IUCN) are the subject of another ***eriss*** research program and are not considered further in this paper. It is worth noting, nevertheless, that in the macroinvertebrate and fish community studies described in this paper for Ranger and Jabiluka, over half of the resources for macroinvertebrate study is spent on sampling of control sites in other independent catchments, while an equal share of the resources for fish study is spent on sampling in independent catchments. Thus, there is a considerable investment to gathering data from across a broad geographical range.

2.2.2 Measured indicators

For the monitoring and assessment programs in the ARR, indicators have been selected to serve the key assessment objectives listed above. For the biological indicators, macroinvertebrate and fish communities, or representative species therein, have been selected for study in the ARR. These groups have been shown in biological assessment programs conducted elsewhere to be particularly sensitive to mine-related disturbances (Humphrey & Dostine 1994). Fish communities also have the advantage in holding a high public profile: they may be an important food resource for some communities and provide important social and cultural amenity. For the two key assessment objectives from section 2.2.1, the following indicators/techniques have been selected:

2.2.2.1 Early detection of short- or longer-term changes

Water chemistry and pre-release toxicity testing:

- physical and chemical indicators, including pH, electrical conductivity, turbidity, uranium, magnesium, manganese and sulphate (see Appendix 1 of this paper for a summary of results for the 2001–02 Wet season);
- plants and animals involved in pre-release toxicity tests. These have been selected from different trophic levels and include unicellular algae, hydra, water fleas and fish fry (Holdway et al 1988, Hyne et al 1996).

Biological monitoring:

- creekside monitoring of reproduction and survival of freshwater snails and survival of fish fry (see Appendix 2 for a summary of results for the 2001–02 Wet season);
- concentrations of chemicals (including radionuclides) in the tissues of freshwater mussels and fish (bioaccumulation) at strategic locations downstream to detect far-field effects including those arising from any potential deposition of mine wastes in sediments; and
- locating sites in a potential ‘disturbance gradient’ such as on and adjacent to the mine site itself. Biota from billabongs on the Ranger mine lease are sampled by ***eriss*** for this purpose.

2.2.2.2 Assessment of biodiversity

- benthic macroinvertebrate communities at stream sites; and
- fish communities in billabongs.

2.2.3 A note on taxonomic resolution

Where biological assessment involves study of benthic macroinvertebrate communities (eg section 2.2.2.2), it is often assumed that species-level identifications will provide greater sensitivity to impacts than where identifications are based upon higher taxonomic levels (eg family-level). Where *impact detection* is the issue, the assumption of greater sensitivity at lower taxonomic levels is based upon the reasonable argument that congeners may vary in their sensitivities to different stressors (eg Cranston 1990). Hence by summarising a response at a higher taxonomic level, critical information may be lost. However, statistical sensitivity also influences the outcomes of these lower vs higher taxonomic level comparisons because precision of the community summaries (eg dissimilarities, taxa richness) used to measure spatial and temporal change may vary according to taxonomic level. In Magela Creek, for example, precision about the mean of paired upstream-downstream dissimilarity indices measured in consecutive years is higher at the family than species level (O'Connor et al 1997) whereas in the upper South Alligator River, this situation is reversed (Humphrey et al 1995a).

In experimental manipulations conducted in the polluted Rockhole Mine Creek, Faith et al (1995) showed that macroinvertebrate species-level data were statistically more sensitive to detecting impact than family-level data. However, the difference in sensitivity between the species-level and family-level analyses was quite small.

Aside from whether or not higher vs lower level taxonomic data provide improved sensitivity for impact detection, identifications to lower taxonomic levels, especially species-level, provide information for biodiversity and conservation assessment. This may be particularly important for sites of high conservation value such as in the ARR. For example, an impact may be detected but what is the ecological importance of this; has any species been 'lost' from the system?

For macroinvertebrates, species-level identifications are much more costly than identifications to higher taxonomic levels (eg family level) and require a considerable skill base. The issue of the appropriate level of taxonomic identification to apply to ARR samples is being reviewed but in the interim, a dual family- and species-level tradeoff will be applied. Family-level data only are being sought from samples collected in control streams, while species-level data are being sought for (upstream and downstream) sites in the receiving waters of concern (Magela Creek near Ranger, and Ngarradj Creek near Jabiluka).

2.3 Experimental design and drawing inference

2.3.1 Basic designs

The strongest class of monitoring and assessment designs are the so-called 'Before–After Control–Impact' family of designs (BACI). The logic that underpins this family of designs is described in ANZECC and ARMCANZ (2000a,b). Use of these designs is strongly encouraged by ANZECC and ARMCANZ (2000a), especially where the opportunity exists to incorporate appropriate spatial and temporal controls. An important embellishment for streams is to use matched pairs of sites (upstream and downstream) in 'potentially-disturbed' and/or control locations (ie BACI-P, where 'P' denotes 'Paired' differences). In this scenario it is the differences between upstream and downstream sites that are compared.

In the ARR, two classes of BACIP design are employed in biological monitoring studies:

1 Simple BACIP design

In this design (Stewart-Oaten et al 1986, 1992, Humphrey et al 1995b), samples are collected simultaneously from single impact and control sites before and after an impact has occurred. The difference between sampled abundances at impact and control areas at any one time is regarded as a replicate observation. For multivariate comparisons (ie community or assemblage data), dissimilarity measures (eg Bray-Curtis measure) may be used as the measure of difference (Humphrey et al 1995b, Faith et al 1995). The means of sets of differences between the two areas before and after are compared by a *t*-test or the equivalent.

2 MBACIP design

In general terms, the M-BACI design of Keough and Mapstone (1995), where 'M' denotes the inclusion of multiple control sites, provides the strongest inferences. The design is an asymmetrical one, using replicated control sites but a single impact site, similar to that described by Underwood (1993). Faith et al (1995), extended this design to the MBACI-P design. Here, similar BACIP 'difference' data are gathered simultaneously and over time, from undisturbed 'upstream' and 'downstream' sites in additional (control) streams. A test for interaction can then be conducted within a multi-factor ANOVA (in particular 'before' vs 'after' impact, 'control' streams vs 'impact' stream).

Whilst there are clear advantages in the MBACIP design (in particular, see Case study presented in Appendix 4, volume 2, ANZECC & ARMCANZ 2000a), the inclusion of additional controls in such designs comes at a considerable cost. In the ARR, fully optimised designs of this type are applied only to 'biodiversity' indicators involving stream macroinvertebrate and fish communities (see previous Guidelines reference for rationale). For fish studies in particular, it is important that control sites are sought in independent streams because fish movement along a stream may confound data analysis and interpretation.

For water chemistry monitoring, a third design and analysis approach is used:

3 Water chemistry monitoring

Compliance for water chemistry variables is based upon a comparison of data from downstream of the Ranger and Jabiluka mine sites with that of baseline or upstream (control) data using a control chart approach. Specifically (Supervising Scientist 2001):

- Three trigger levels are set in accordance with the distributional properties of baseline data from which they are derived.
- For normal distributed baseline data, and with the exception of pH, trigger levels are +1, 2 and 3 standard deviations (σ) from the mean for 'focus', 'action' and 'limit' 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 80th percentile ('focus'), the 95th percentile ('action') and a maximum ('limit') which in the case of U is a site-specific, biological-effects value derived in accordance with the new Water Quality Guidelines (ANZECC & ARMCANZ 2000a) from toxicity testing of local aquatic species (van Dam 2000).
- Trigger values have yet to be set for Mg or SO_4 in Magela Creek downstream of Ranger. New values are currently being determined on the basis of site-specific, biological-effects data (as per derivation of U trigger value). Until these new values are available, the trigger values for electrical conductivity are used as surrogate indicators because, in most cases, elevated conductivity measured downstream of Ranger is attributable to Mg and SO_4 released from the mine.

  Triggers for $_{226}$Ra in surface waters are defined for human radiological protection purposes and are summarised in section 3.2 below.

2.3.2 The status of environmental controls

The ability to employ optimal designs to infer strong inferences about possible mining impact in the ARR is tempered and constrained by a number of factors:

(i) Pre-mining (1980), baseline data are sparse for Magela Creek downstream of Ranger — reducing the inferential capacity of monitoring designs (Humphrey & Pidgeon 1998).

(ii) Some water chemistry samples gathered from Magela Creek as part of the monitoring regime that was in place prior to the establishment of the SSD's monitoring program (ie pre-2000) were analysed using techniques with poor detection limits and QA/QC procedures.

(iii) Research and development for macroinvertebrate and fish community monitoring techniques have occurred over a relatively lengthy period (Humphrey & Pidgeon 1998). The current, 'optimal' design for macroinvertebrate study, for example, has only been in place since 1998; trends in community summaries calculated between upstream and downstream sites in Magela Creek over the period 1988 to the present may be artefacts due to changes in technique.

(iv) Designs using fish communities that are confined to a single stream (eg pre-1994 data for Ranger) may be confounded by fish movement along the stream.

(v) The extent of spatial and temporal control data in the ARR is governed more by constraints of resources and availability/suitability (of controls) than by prospective power analysis that would assist in determining such matters. The number of control sites and amount of control data are compatible with default recommendations provided in ANZECC and ARMCANZ (2000a).

The Jabiluka monitoring program is aimed at both acquiring baseline data and, given the current development and infrastructure in place, determining (through monitoring) whether the Environmental Requirements are being met. Given that any further development of the mine has been delayed indefinitely, there is ample opportunity to gather adequate baseline using optimal designs.

2.3.3 An appropriate level of monitoring?

Because pre-mining, baseline data are sparse for Magela Creek downstream of Ranger — reducing the inferential capacity of monitoring designs — the monitoring program has had to compensate for this, incorporating additional indicators and sampling sites where required in a *weight of evidence* approach. As discussed and recommended in ANZECC and ARMCANZ (2000a), a 'weight of evidence' approach to inference places emphasis on enhancing the monitoring battery, ie selecting and including additional sites, biological indicators, chemical monitoring, and toxicological and other experimental data in which concordance is sought between field results and controlled experimental findings. Such an integrated assessment approach will better enable correct inferences about impact to be made. The amount of monitoring conducted for the Ranger mine is consistent with the approach recommended by ANZECC and ARMCANZ (2000a) for 'Sites where an insufficient baseline sampling period is available' (section 7.2.1 of the Guidelines).

2.3.4 Data analysis procedures

A suite of analysis procedures are being incorporated in the monitoring protocols, including:

- Formal hypothesis testing for BACIP and MBACIP designs. For MBACIP approaches with few temporal data, single-factor ANOVA (control streams vs impact stream) of univariate and multivariate variables will be applied until sufficient data are available.
- Control chart approaches to chemical and radionuclide data, where limits for ecosystem or human health have been set.
- Plots of the accruing time series of (raw or 'difference') data to portray any trends and assist in data interpretation. Biological data will be compared with associated water chemistry data; chemical data will be used as covariates of biological responses where applicable. Variation may be modelled using natural environmental variables or mine-disturbance variables (ANCOVA).
- For community data, multivariate ordination of the full data-set. (Does the downstream 'impact' site lie within the space occupied by other sites?)
- Assessment of the biodiversity and conservation status of the fauna of 'to-be-disturbed' streams (arising from the species-level analyses).

In addition, prospective power analyses is being undertaken of current fish and macroinvertebrate community data to ensure that the designs are optimised as far as possible.

3 Radionuclide monitoring

Concentrations of radionuclides of the uranium decay series are elevated in mine materials (including pond waters) at Ranger and Jabiluka, in comparison with concentrations in the surrounding environment. Consequently, monitoring of radionuclide concentrations in biota, surface waters, ground waters, sediments and the air is carried out for two purposes:

- for protection of humans from the potentially harmful effects of radiation; and
- as indicators of the transport of mine materials into the environment.

The SI unit of radioactivity is the becquerel (Bq), which is defined as an average atomic disintegration rate of one per second.

Background material on the protection of humans from radiation may be found at
www.ea.gov.au/ssd/uranium-mining/research/protect/index.html and
www.ea.gov.au/ssd/faqs/radiation.html.

3.1 Radionuclides in biota

Past research has shown that the primary pathway leading to radiation exposure to humans following release of mine wastewaters into the Magela Creek or Ngarradj is uptake of the radionuclide radium-226 (Ra-226) by the freshwater mussel *Velesunio angasi*. This is due to the high concentration (or bioaccumulation) factors for radium in these mussels, and the fact that they form part of the traditional diet of Aboriginal people in the Region. As part of the monitoring program, samples of the edible flesh from a number of mussels is dried, combined and prepared for counting by gamma-ray spectrometry using HPGe detectors. Results for Ra-226 concentration are reported as Bq/kg of the dried tissue.

3.2 Radionuclides in creek waters

Concentrations of the radionuclide Ra-226 are measured by alpha-particle spectrometry. Results are reported in units of mBq/L.

Triggers for Ra-226 in surface waters are defined for human radiological protection purposes and apply to the increase above natural background in Ra-226 concentration in surface waters downstream of Ranger and Jabiluka. Focus level, action level and limit are, respectively, >10 mBq/L, >10 mBq/L over 90 consecutive days, and annual average of 10 mBq/L. The limit for Ra-226 is based on the following:

- a dose constraint of 0.3 mSv per year above natural background from the ingestion of Ra-226 in freshwater mussels
- a 10 year old child consuming 2 kg of mussels annually, and
- a concentration factor for mussels of 19 000 for Ra-226.

In drawing a conclusion that exceedance of the limit for Ra-226 constitutes a breach of the Ranger Environmental Requirements, the Supervising Scientist must be convinced that the anthropogenic dose to the critical group has exceeded 1 mSv in one year.

3.3 Radionuclides in creek sediments

Over the long term, any radionuclides released into creek systems will deposit on sediments downstream. For monitoring purposes, surface scrape samples are collected annually from locations where such deposition is expected to occur. Analysis is by gamma-ray spectrometry using HPGe detectors. Results for Ra-226 concentration are reported as Bq/kg of the dried sediment.

3.4 Radionuclides in bore waters

Of the radionuclides of the uranium decay series, only Ra-226, U-238 and U-234 are of potential concern with regards to the groundwater pathway. This is because other members of the decay series would not be expected to migrate significant distances in groundwater aquifers either because of their short halflife or because of the chemistry of the element concerned. In the case of Ra-226, previous research carried out by ***eriss*** at Ranger showed that radium concentrations in the groundwater are dominated by localised effects dependent on concentrations of other solutes in the water rather than migration of radium through the aquifer (Martin & Akber, 1996).

Consequently, the borewater monitoring program is focussed on concentrations of the uranium isotopes. Samples are collected once per year from selected bores and analysed for U-238 and U-234 by alpha-particle spectrometry. Samples are filtered prior to analysis since it is the concentration in solution which is of interest in terms of uranium migration. Concentrations are reported in units of mBq/L. Concentrations of U-238 may be converted to units of μg/L of uranium by use of the following conversion factor:

1 mBq/L U-238 = 0.081 μg/L uranium

3.5 Radon and radon progeny

Radon-222 (Rn-222, halflife 3.82 days) is an isotope of radon, an inert gas. It is continually exhaled from the Earth's surface, however since it is a member of the uranium decay chain the exhalation rate per unit area from uranium mine materials is generally greater than that from most environmental soils. Once released from the ground surface, Rn-222 is dispersed in the air and remains in the air column until it decays to a number of short-lived radioactive progeny (or "daughters"). In contrast to radon gas, which is exhaled again after inhalation, some of the radon progeny is retained in the soft tissue of the lungs and their subsequent alpha-decay delivers a dose to the respiratory system. Therefore, it is the inhalation of the radon progeny that gives rise to the majority of the dose to people arising from the presence of radon in the atmosphere.

eriss maintains a permanent radon and meteorological station at a location approximately 1 km west of Mudginberri billabong. This location was chosen because of the permanent occupation at Mudginberri by a group of Aboriginal people, and because it is approximately mid-way between the Ranger and Jabiluka sites.

Monthly average Rn-222 concentrations are reported in units of Bq/m^3. In addition, measurement of radon progeny potential alpha energy concentration are measured at the Mudginberri station site, Jabiru and Jabiru East on a monthly basis for 24 hours, as those are the major population centres in the park, and reported in units of µJ/m^3. The radon decay product data obtained by ***eriss*** are regularly compared with data reported by ERA in their Quarterly Radiation Protection and Atmospheric Monitoring Reports.

Radon and radon progeny concentrations are higher during the dry season than during the wet season due to a number of factors. These include the frequency of storms with associated turbulent atmospheric conditions in the wet season, and lower radon exhalation rates from the ground surface in the wet season due to the higher soil moisture content.

3.6 Radionuclides on airborne dust

Similar to the inhalation of radon progeny, the inhalation of radioactive elements 'trapped' in or on dust which is retained in the lungs can deliver a radiation dose to the respiratory system. This dust inhalation is referred to as exposure to long lived alpha activity (LLAA), as the members of the uranium decay chain are in secular equilibrium with their relatively long-lived radioactive progenitors, Ra-226 ($t_{1/2}$ = 1 600 yr) for mill tailings dust and U-238 ($t_{1/2}$ = 4 500 million yr) for ore dust, respectively. Dependant on its activity median aerodynamic diameter (AMAD), dust stirred up on the mine site by natural processes or blasting can be transported beyond the boundaries of the mine and inhaled, although there is no evidence of significant transport of heavy metals beyond the mine lease (A. McKenzie, 1991).

Dust is collected for periods of one week per month at the Mudginberri station site, Jabiru and Jabiru East. After collection, Rn progeny is allowed to decay on the filter paper for a period of > 2 days and the alpha disintegrations per second of the dust collected are measured with a gross alpha counter. LLAA are reported in units of Bq/m^3. The LLAA data obtained by ***eriss*** are compared with data reported by ERA in their Quarterly Radiation Protection and Atmospheric Monitoring Reports.

4 Dispersion of mine waste waters to streams in the ARR

4.1 Ranger mine

4.1.1 Magela Creek

Two sites were monitored in Magela Creek, one upstream of mine-related influence and one approximately 6 km downstream of the mine at the statutory monitoring point at gauging station GS8210009 (commonly termed 009). The latter monitoring point is situated a short distance upstream of the Ranger project area boundary. The GS0009 site is convenient for monitoring because water quality upstream of this point is influenced by no other anthropogenic activities than mining at Ranger. These monitoring stations together with relevant sources of mining effluent are depicted on the Ranger mine sampling points map.

The primary host rock for uranium mineralisation at Ranger is Cahill Schist. Uranium ore and associated waste rock (mostly schist) contain small quantities of sulphide minerals (mainly iron sulphides, with minor amounts of copper and lead sulphides). The sulphide minerals were formed in association with carbonate minerals, which in the case of the Ranger orebody have largely remained in close proximity to the sulphides. This is a fortuitous circumstance, as it minimises the occurrence of acid rock drainage, which is not a management issue at Ranger. Mine effluents at Ranger almost invariably have near-neutral pH values.

The principal waste products from the Ranger site are magnesium, sulphate ion, uranium, and calcium. Although ore and waste rock include some copper and lead contents, these metals are not very mobile and have not been reported at concentrations of environmental concern.

Magnesium and sulphate ions derive from the oxidation of sulphide minerals and simultaneous hydrolysis of magnesite and calcite, which also produces a lesser quantity of calcium. These minerals are contained within waste rock. Some magnesium is released from the weathering of other minerals, such as chlorite, a micaceous mineral which is a component of the host schist. Uranium is believed to derive principally from the weathering of carbonate minerals that contain a small proportion of this element. In this chemical environment uranium is reasonably mobile and thereby reports in low concentrations in effluent flows. The uranium-containing carbonates are a component of waste rock.

The main source of mine-related effluent is Retention Pond 1 (RP1) from which uncontrolled release occurs to Coonjimba Billabong via a weir. Overflow usually occurs from December/January until May each year. Uncontrolled discharge also occurs via Georgetown Billabong to Magela Creek. Mine contaminants originate from waste rock near the eastern margins of the mine site and enter Corridor Creek, then Georgetown Billabong. The quantity of mine contaminants discharged through Georgetown Billabong is usually lower than via the RP1 route. Two additional pathways for contaminant release from the mine are by controlled release of waste-rock runoff through Djalkmara Billabong, and by washoff from the Magela land application area. In both cases, contaminant burdens are typically a small fraction of the flux through Coonjimba Creek from RP1.

4.1.1 Gulungul Creek

Two sites were monitored in Gulungul Creek (see Ranger mine sampling points map). The upstream site is at the Ranger project area boundary. The downstream site is slightly upstream of the point where the creek flows through the Arnhem Highway culvert. Gulungul Creek may receive mine-related effluent from two sources: (i) surface expression of groundwater, which originates from tailings-dam seepage to the shallow (C-horizon) aquifer; and (ii) overland flow of runoff from the waste-rock external surface of the tailings dam. The groundwater source should contain only magnesium and sulphate, uranium and other heavy metals being relatively immobile in groundwater. Contaminants from overland flow will contain the signature of whatever components were contained in the original runoff, possibly with some attenuation of less-mobile constituents (such as uranium), depending on transit time to the creek.

4.2 Jabiluka mine site

Two sites on Ngarradj Creek were monitored, one upstream of the minesite and one downstream. Both sites are located at gauging stations (see the Jabiluka mine sampling points map). Current water management at Jabiluka would generate uranium-dominate effluents, if any release were to occur. Waste water currently stored at the site has relatively low magnesium and sulphate burdens. The exact mechanism for effluent entry into Ngarradj Creek would depend on management practice, but would likely be carried dominantly by North Tributary, with some contribution from Central Tributary.

The host rocks at Jabiluka are very similar to those at Ranger. The main difference is that the contents of uranium, and other components of the mineralised rock, are about 50% higher than at Ranger. However, as the quantity of mineralised material brought to the surface at Jabiluka is much smaller than at Ranger, the pattern of effluent contaminants is different at Jabiluka, although their identity is the same. Most contaminated water held at the surface at Jabiluka comes from the decline (the tunnel excavated to the ore body). This water has an elevated concentration of uranium, but much lower concentrations of magnesium and sulphate than comparable waterbodies at Ranger. This will affect the relative concentrations of contaminant species in the event of any environmental release.

5 Ranger monitoring program

This section provides a brief description of the elements of the Ranger monitoring program. Management goals and hypotheses associated with assessment of mining impact upon ecosystems are coached around the objective of ‘no change to biological diversity’.

5.1 Early detection of harmful effects

Rationale: Used for the **early detection** of harmful far-field effects arising from dispersion of mine waste waters; radionuclide and bioaccumulation studies are also used for the **protection of human health**.

5.1.1 Water and sediment monitoring program

Chemical (including radionuclide) monitoring is being conducted in Magela Creek and tributaries in the period of flow in the creeks in order to (i) enhance the baseline/background dataset for water chemistry upstream of Ranger, and (ii) detect potential mine-related ‘perturbations’ and isolate their source. The specific indicators to be measured, sampling sites and sampling frequencies and data analysis procedures are described in section 2.2.2.1, Appendix 1 and section 2.3.1/3 respectively.

At this stage, sediment sampling and monitoring are limited to annual samples gathered downstream of Ranger for radionuclide analysis.

5.1.2 Creekside monitoring

Creekside monitoring is conducted at two sites in Magela Creek, upstream and downstream of the Ranger mine. Several four-day tests are conducted per wet season using larval black-banded rainbowfish survival test and freshwater snail egg production test. Further details are provided in Appendix 2 while data analysis procedures are described in section 2.3.1/1.

5.1.3 Bioaccumulation in fish and freshwater mussels — Mudginberri Billabong

Mudginberri Billabong is the first major, permanent waterbody (12 km) downstream of Ranger. Local Aboriginal people harvest aquatic food items from the billabong and hence it is essential that the fish and freshwater mussels from the billabong in particular are fit for human consumption. Enhancement of metal and radionuclide concentrations would also serve as early warning of the bioavailability of mine-dispersed wastes well off-site.

Fish metal burden data are sparse. Mussel metal and radionuclide data from Mudginberri are historically more extensive but intermittent; early (1980s) metal data in mussels may suffer from QA/QC problems arising from the outsourcing of chemical analyses. From 2002, metal and radionuclide concentrations in biota will be gathered from Mudginberri and a comparable control billabong in another catchment annually (mussels) or every other year (fish). Data analysis procedures will be a combination of those described in section 2.3.1/1 and section 2.3.1/3.

5.2 Natural communities for assessing ecological importance of impacts

Rationale: Used for monitoring and assessing changes to **biological diversity** in Magela Creek as a consequence of dispersion of mine waste waters.

5.2.1 Macroinvertebrate communities

Sampling is conducted annually at 2 or 3 sites in each of Magela Creek and three control streams (Baroalba, Gulungul and Nourlangie creeks) using a MBACIP design (section 2.3.1/2). As described in section 2.3.2/(iii), there are no true baseline data for this study and there have been changes in methodology since 1988. Some of the data analysis procedures described in section 2.3.4 may assist in interpretation of results from this study.

5.2.2 Lowland billabong fish communities

Sampling is conducted in late April-end June of each year. Two types of data are gathered, using non-destructive sampling methods:

1. Visual observation data from deep, channel billabongs: Mudginberri Billabong (‘exposure’ billabong, Magela Creek downstream of Ranger, 1989–present); Sandy Billabong (control billabong, Nourlangie Creek, 1994–present).
2. Data from ‘pop-nets’ set in shallow, weedy, lowland billabongs, in various combinations, 1994 to present:
    - ‘exposure’ billabongs in Magela Creek downstream of Ranger
    - ‘unexposed’ billabongs in Magela Creek (‘pseudo’-controls)
    - ‘unexposed’ billabongs in Nourlangie Creek (true controls)

The design for both approaches is amenable to BACIP (though as with other Ranger techniques, ‘Before’ data have been gathered well into the operational phase of mining): 1) exposure billabong(s) vs control billabong(s) from independent catchment; 2) ‘exposed’ billabongs vs ‘unexposed’ billabongs in Magela Creek, recognising that this second approach is confounded by possible movement of fish between the two billabong types.

In 2000 and 2001, the sampling methods were modified to meet OH&S (crocodile) safety requirements. The modifications are believed not to have compromised the data and data continuity over time.

6 Jabiluka monitoring program

This section provides a brief description of the elements of the Jabiluka monitoring program. Management goals and hypotheses associated with assessment of mining impact are coached around the objective of 'no change to biological diversity'. To be in a position to detect and assess change should mining commence, adequate baseline data must be gathered. While gathering of pre-mining, baseline data is the main focus of this program, monitoring is also required because there is some existing disturbance (albeit very small) arising from the mine site. Runoff from the mine site enters Ngarradj Creek.

An intensive 3–4 year period of data gathering has been completed in which macroinvertebrate community samples and water samples for chemical analysis were gathered at regular intervals throughout the Wet seasons (1998 to 2001). From the 2001–02 sampling season and beyond, the intensity of baseline sampling program is being reduced for these indicators. Baseline data on fish communities and bioaccumulation in fish are not as extensive as those for water chemistry and macroinvertebrates and so baseline sampling for these aspects will continue as for previous years. This entire program will continue on an annual basis for the next several years at least.

6.1 Early detection of harmful effects

Rationale: Used for the **early detection** of harmful far-field effects arising from dispersion of mine waste waters; radionuclide and bioaccumulation studies are also used for the **protection of human health**.

At this stage there are no plans to set up creekside facilities at sites on Ngarradj Creek until there is better information about water quality issues and the proposed water management strategy for any future mine operation at Jabiluka.

6.1.1 Water and sediment monitoring program

Chemical (including radionuclide) monitoring is being conducted in Ngarradj Creek and tributaries draining the minesite in the period of flow in the creeks in order to (i) enhance the baseline/background dataset for water chemistry upstream of Jabiluka, and (ii) detect potential mine-related 'perturbations' and isolate their source. The measured indicators, sampling sites and sampling frequencies and data analysis procedures are described in section 2.2.2.1, Appendix 1 and section 2.3.1/3 respectively.

At this stage, sediment sampling and monitoring are limited to annual samples gathered in Ngarradj Creek for radionuclide analysis.

6.1.2 Bioaccumulation in fish — Ngarradj and Catfish creeks

Fish metal burden data are being gathered twice annually from Ngarradj ('exposed') and Catfish (control) creeks. Data analysis procedures will be a combination of those described in section 2.3.1/1 and section 2.3.1/3.

6.2 Natural communities for assessing ecological importance of impacts

Rationale: Used for monitoring and assessing changes to **biological diversity** in Ngarradj Creek as a consequence of dispersion of mine waste waters.

6.2.1 Macroinvertebrate communities

Paired sites have been sampled on a monthly basis during the past three wet seasons from Ngarradj and three control streams. A MBACIP design may be applied to the data (section 2.3.1.2), despite some disturbance to Ngarradj Creek catchment during the early baseline gathering phase. Davidson (2000) conducted a study in the 1998–1999 Wet season designed to detect and assess any effects of enhanced turbidity arising from the disturbed Jabiluka mine site. (There was no evidence of any adverse effects upon macroinvertebrate communities in the receiving waters of Ngarradj Creek.) From 2002 onward, monthly wet season sampling has been confined to Ngarradj and one control stream (Catfish Creek), though end-of-wet sampling (April) is being conducted across the full suite of sites (four streams).

An access road proposed to be constructed between Ranger and Jabiluka will intersect the paired sites in two of the control streams (North Magela and 7J creeks). As a contingency, an additional site has been sampled in April, in each creek above the proposed road crossing (thereby creating a pair of potentially undisturbed sites in each creek).

6.2.2 Fish communities in streams and billabongs

Sampling is conducted in the period March to end of June of each year. Two types of data are gathered, using non-destructive sampling methods:

1. Data from 'pop-nets' set in shallow, weedy, lowland billabongs, in various combinations, 1994 to present. This is incorporated in the Ranger design (end-of-wet sampling), described above (section 4.2.2):
   - Winmurra Billabong 'exposure' billabong (may potentially be disturbed by Ranger-Jabiluka mine haul/access road)
   - Cathedral Billabong, 'unexposed' billabong in East Alligator catchment.
   - 'unexposed' billabongs in Nourlangie Creek (true controls)
   - 'unexposed' billabongs in Magela Creek ('pseudo'-controls)
2. Paired sites have been sampled in each of March and April during the past four wet seasons from Ngarradj and three control streams (same sites as macroinvertebrate study). Data from visual surveys and dip-netting conducted at each site and on each sampling occasion are combined for data analysis.

The design is amenable to: 1) BACIP for both approaches where exposure billabong/sites are compared with control billabong(s)/sites from independent catchments; and 2) imperfect MBACIP using paired sites in Ngarradj and three control streams — recognising that this second approach is confounded by possible movement of fish between the paired sites of each creek.

7 Issues associated with implementing the monitoring program

Humphrey et al (1999) discuss aspects of implementation of routine monitoring programs in the ARR, including:

- preparation of rigourous protocols for program design, field and laboratory procedures;
- aspects of data management, documentation and reporting; and
- stakeholder involvement.

Several key issues associated with implementation include:

7.1 Protocols

Streamlined processes supplying precise, accurate and rapid results are required for the ARR monitoring programs that will provide early warning to management and interested stakeholders of unacceptable impacts. To enable rapid feedback of monitoring results, protocols have been prepared, or are being finalised or reviewed, for all field and laboratory procedures, including data management.

Generic subject headings used in the biological monitoring protocols include, for example:

1 Introduction and monitoring objective
2 Experimental design
   Principle of the monitoring design
3 Field sampling
   Equipment
   Collection of biological samples
   Collection of environmental data
4 Laboratory sample processing
   Sorting, specimen identifications and subsampling
   Processing of chemical samples
5 Data compilation, statistical analysis and interpretation of results
   Database entry and software
   Statistical treatment of data and testing for impact
6 QA/QC
7 Sample and data storage
8 References

7.2 Reporting

A pro forma for reporting and disseminating information to stakeholders and other users is being considered for the ARR monitoring programs. A suitable template and checklist for these aspects is provided in the new Monitoring and Reporting Guidelines (ANZECC & ARMCANZ 2000b; in particular, Chapter 7, ‘Reporting and Information Dissemination’).

Appropriate recommendations arising from ANZECC and ARMCANZ (2000b) as well as internal considerations, include:

- The reporting of interim results on a monthly, bimonthly, quarterly or six-monthly basis, depending upon the technique and its feedback requirements, eg water quality and early detection data will need to be transmitted rapidly to the end-users of the data, eg within days or weeks.

- An annual report for each technique would be provided, each report containing Summary, introduction, experimental detail, results, discussion of the results including data interpretation and implications for management, conclusions and appendices containing laboratory reports, data tables or other information that is too detailed or distracting to be included in the main body of the report. The reports would contain necessary data summaries and graphical presentations of results.

- Summary versions of the main report may be required for different end-users with the information conveyed to them in the most appropriate form. Those provided to local Aboriginal groups in the ARR would need to be written in less technical, plain English form eg format and style of current Newletters that are provided to Aboriginal groups on a regular basis.

- The annual reports and summaries would be staggered in their production, the results from early detection methods being provided to end-users before the results of other techniques. For some techniques, laboratory processing is a lengthy process, eg macroinvertebrate and environmental radioactivity studies, and so reporting may be unavoidably delayed.

7.3 Communication strategy

ARR stakeholders include the Aboriginal Traditional Owners of the area, other resident Aboriginal people, Commonwealth and Northern Territory governments, ERA and the general public. ***eriss*** and the ***oss*** report on the environmental monitoring results through groups such as the Alligator Rivers Region Advisory Committee (ARRAC), ARRTC and Ranger and Jabiluka Minesite Technical Committees (MTC). Consultation and reporting of monitoring results to stakeholders and the wider community would be carried out in cooperation with the ***eriss*** Research Support and Communication section.

Methods for information reporting and dissemination have yet to be devised. Suitable approaches would include:

- Written reports pitched at the appropriate technical level;
- Presentations to local stakeholders, eg Open days and site visits, Aboriginal Association meetings, ARRAC, ARRTC and MTCs. In the case of local Aboriginal people, the NLC would assist in liaising with relevant groups;
- Film and video presentations may be effective, particularly for local Aboriginal people; and
- Web site.

All communication strategies, including media releases, media articles and dissemination of information outside of the ARR, need to have the approval and clearance of the Supervising Scientist.

7.4 Aboriginal involvement

Dissemination of information in a timely manner to local Aboriginal groups will be a particularly important aspect of reporting and communication for the new monitoring programs in the ARR. These aspects are mentioned above. Another key commitment ***eriss*** has made to the monitoring programs is the involvement and employment of local Aboriginal people in the work programs themselves. This is already a feature of the research programs at ***eriss*** and these aspects will be consolidated as the monitoring programs develop further. Apart from much needed assistance, cultural insights to the monitoring programs and the building of trust, such employment opportunities also provide excellent mechanisms to communicate monitoring results to the broader Aboriginal community of the ARR.

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