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eriss research summary

2004–2005

KG Evans, J Rovis-Hermann,
A Webb & DR Jones (editors)

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 summary of the 2004–05 research program of the Environmental Research Institute of the Supervising Scientist and has been reviewed internally by senior staff and the editors of the volume.

Kenneth G Evans – Environmental Research Institute of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia.

Jacqui Rovis-Hermann – Office of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia. (Current address: Department of Employment & Workplace Relations, 11th Floor, QV1 Building, 250 St George's Terrace, Perth WA 6000, Australia)

Ann L Webb – Office of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia.

David R Jones – Environmental Research Institute of the Supervising Scientist, GPO Box 461, Darwin NT 0801, Australia.

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Contents

Preface

The Environmental Research Institute of the Supervising Scientist (***eriss***) is part of the Supervising Scientist Division of the Commonwealth Department of Environment and Heritage. Its primary role is to undertake monitoring of and research into the impact of uranium mining activities in the Alligators Rivers region to protect human and ecosystem health, and to provide advice to the Supervising Scientsist. ***eriss*** also conducts research on tropical river systems and the ecology and conservation of tropical wetlands with a focus on the sustainable use of water resources.

This report contains summaries of research projects undertaken by ***eriss*** over the 2004–05 financial year. For additional information, readers are referred to the annual publications list (Appendix 1) which details all of the material published, and conference and workshop papers presented by ***eriss*** staff in 2004–05.

The balance and strategic prioritisation of work within the uranium component of ***eriss***'s project portfolio is defined by Key Knowledge Needs (KKNs) developed by consultation between the Alligator Rivers Region Technical Committee (ARRTC), the Supervising Scientist, Energy Resources of Australia and other stakeholders. Six thematic areas (based primarily on geographic provenance) have been identified as being the primary KKN's topic areas to ensure the current and future protection of the environment of the Alligator Rivers Region (Appendix 2). The content of the research program developed for each of these areas is assessed and reviewed annually by ARRTC in consultation with stakeholder groups.

Each of the thematic areas comprises research themes for assessing current (operational) status by monitoring and for developing the requirements, procedures and practices needed to rehabilitate the terrestrial and aquatic ecosystems within the disturbed footprint to a state consistent with the World Heritage values of Kakadu National Park. A critical outcome of the research on rehabilitation aspects will be defensible closure (relinquishment) criteria and the identification and prioritisation (in both technical need and time dimensions) of post closure monitoring programs.

The list of KKNs and research themes identified for 2004–05 are detailed in Appendix 2. The research themes provide the basis for defining the specific project activities to be carried out from year to year.

eriss contributes to the addressing of the KKNs by applying its expertise in:

- Ecotoxicology
- Environmental radioactivity
- Hydrological and geomorphic processes
- Monitoring and ecosystem protection
- Biophysical pathways and ecological risk assessment
- Aquatic chemistry

Not all of the KKN research areas are able to be covered by ***eriss***, since not all of the required disciplines are available within the Institute. To address these gaps, collaborative projects have been initiated with researchers from other organisations such as Charles Darwin University and Earth Water Life Sciences Pty Ltd (the technical consulting business unit of Energy Resources of Australia Ltd). The outcomes from such collaborations are included in this report. KKN projects related to hydrogeology or tailings management are conducted by other organisations.

This report has been structured under five main headings, consistent with the KKN framework:

1 Ranger – Current Operations

2 Ranger – Rehabilitation

3 Jabiluka

4 Nabarlek

5 General Alligators Rivers Region

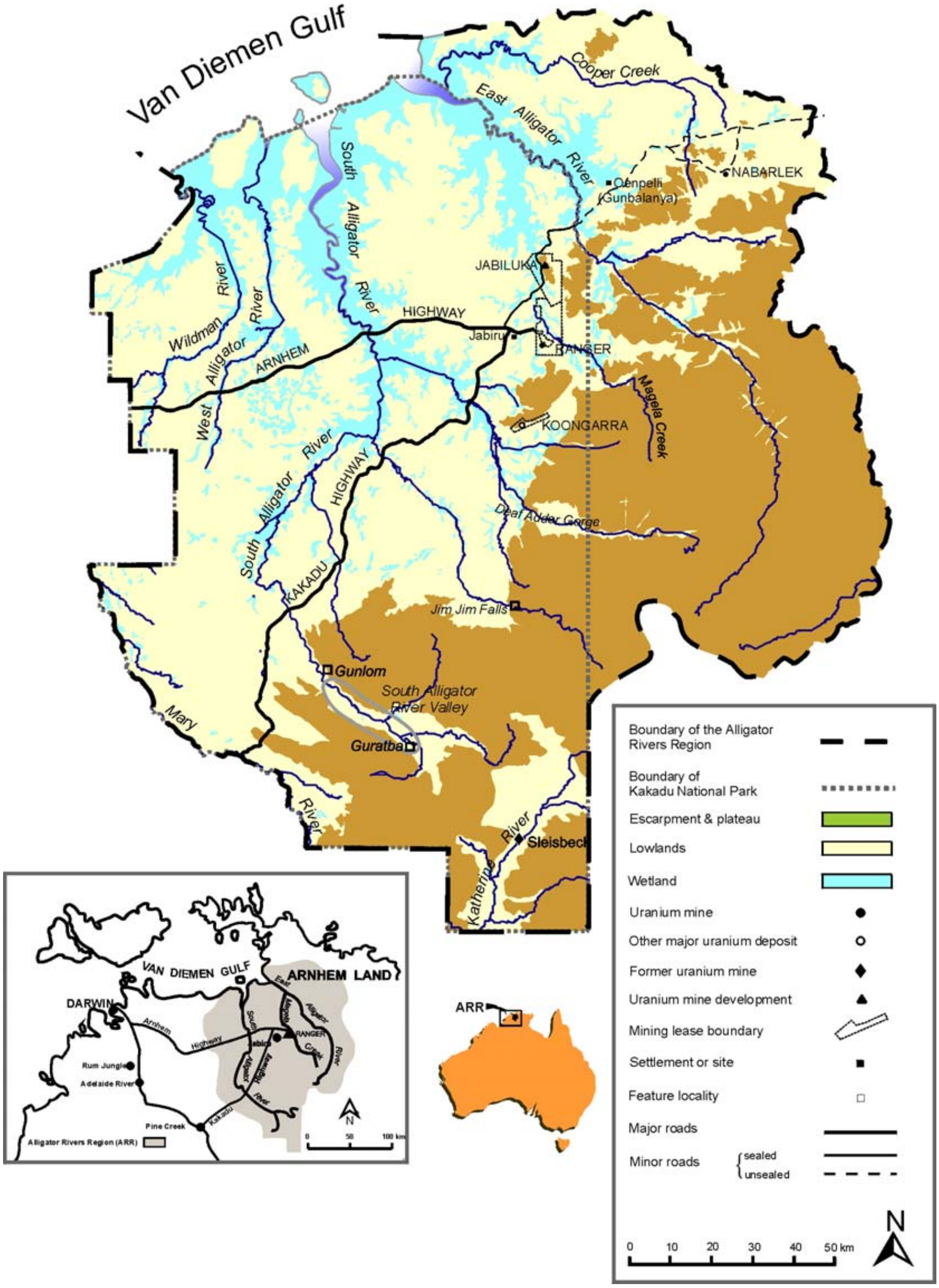
The sixth KKN – Knowledgement Management and Communication – has not been included as a specific section since many of the theme areas are embedded in the project approvals process and in the work programs for the projects that have been described. For examples, the intent of KKN 6.6.1 (Appendix 2) is addressed by the report on Ecological risk assessment of the Magela floodplain' in Part 5. Communication between research providers (KKN 6.3) is being addressed by stakeholder presentations and interactions at ARRTC meetings, as well as by conduct of formal multistakeholder workshops. Communication with local Indigenous people and other regional stakeholders is an integral part of the project approvals process. A dedicated Aboriginal Communications Officer is stationed at Jabiru for this purpose. The outcomes of research projects are also communicated to local peoples by this route.

Three maps (following this Preface) provide the regional context for the locations referenced in the KKN research reports. Map 1 shows Kakadu National Park and the locations of the Ranger Mine, Jabiluka project area, the decommissioned Nabarlek Mine, and the South Alligator River Valley. A schematic of the Ranger mine site is provided for reference in Map 2. Map 3 shows the locations of billabongs and waterbodies used for the aquatic ecosystem monitoring and research programs for assessing impacts from the Ranger Mine.

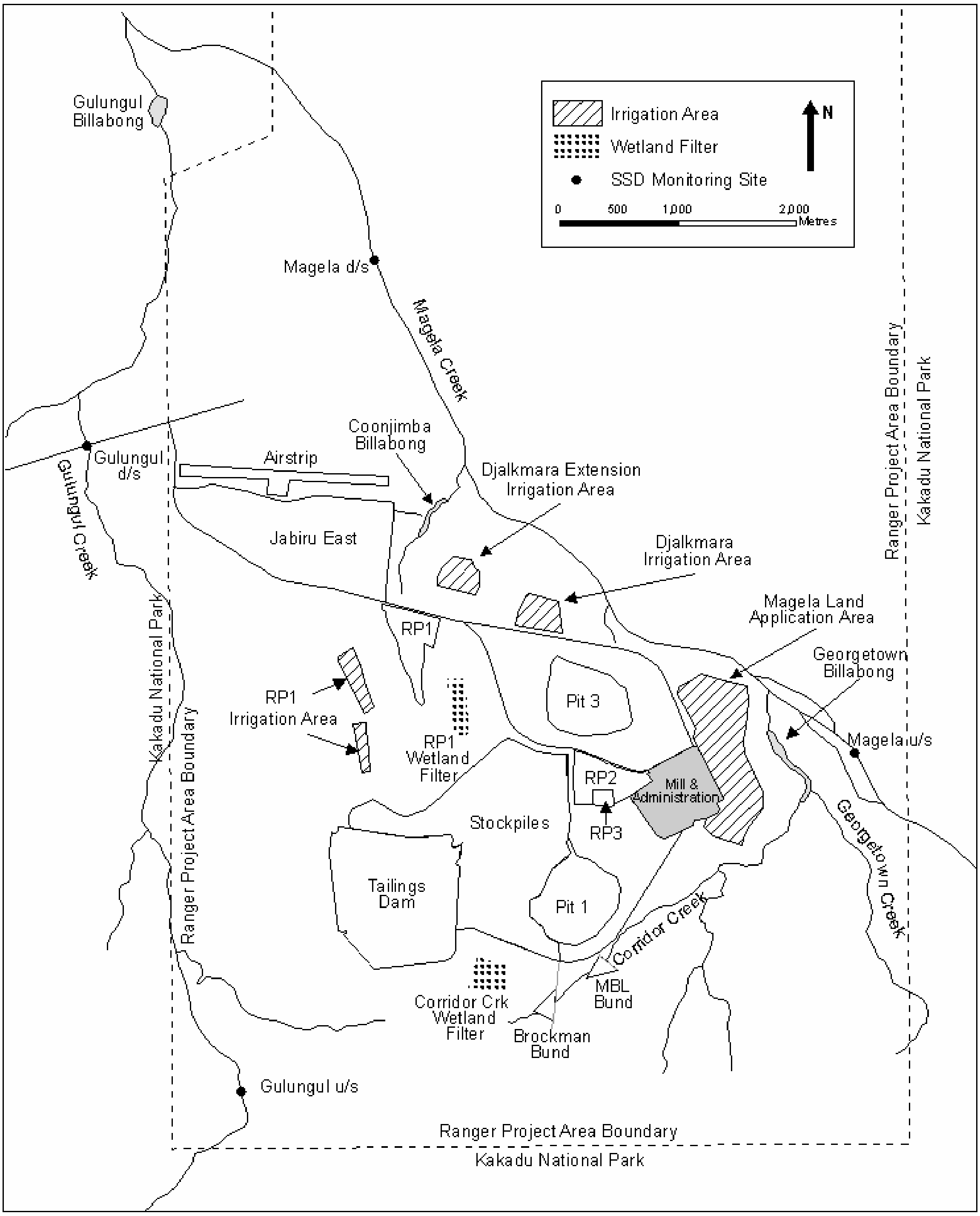
The final part of the report contains a summary of non-uranium mining related external projects carried out by ***eriss*** during 2004–05. Commercial-in-confidence projects have been excluded from this compilation.

Dr DR Jones

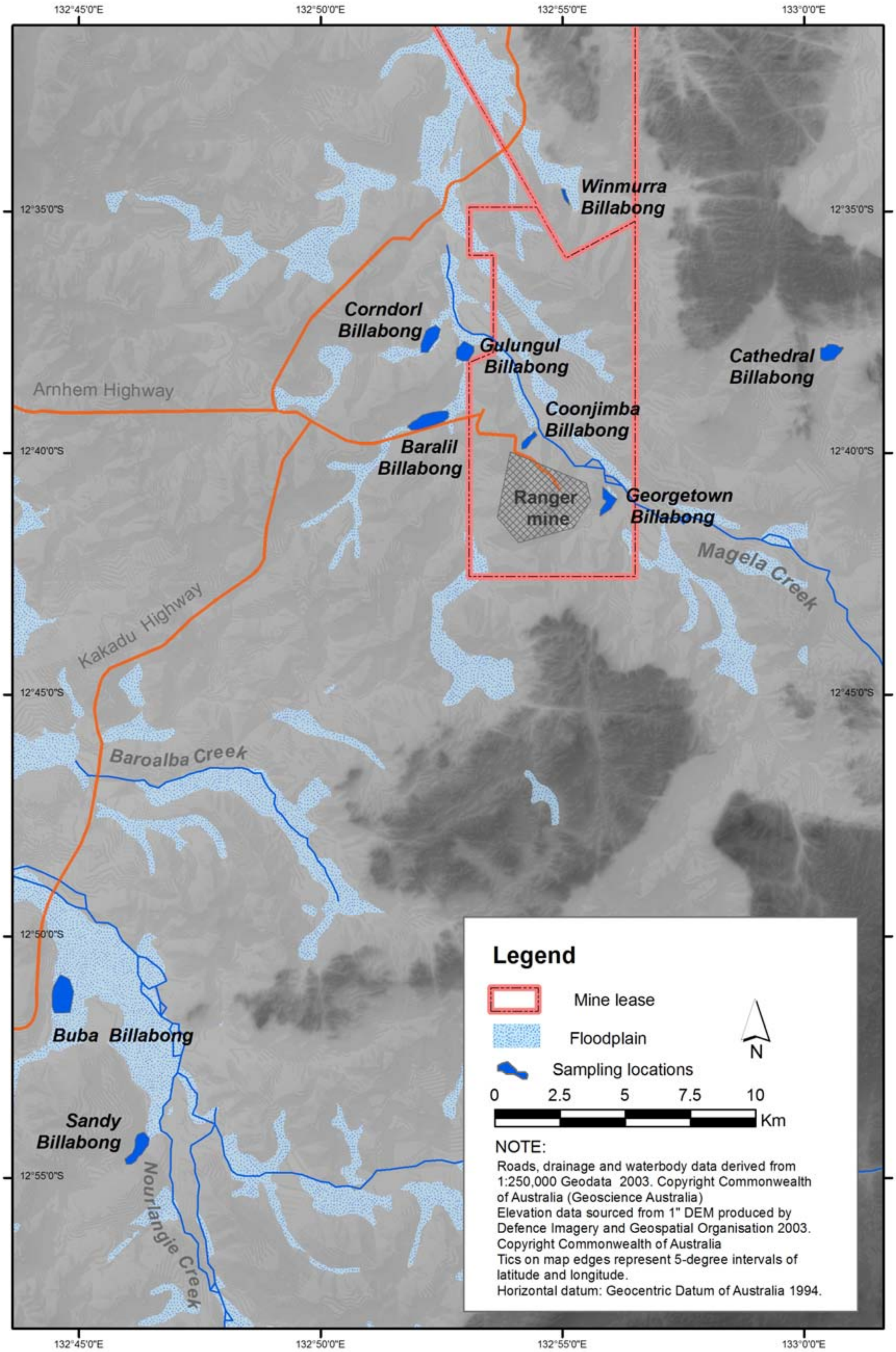
Director, Environmental Research Institute of the Supervising Scientist



Map 1 Alligator Rivers Region



Map 2 Ranger mine site



Map 3 Locations of mine site and reference billabongs used for biological sampling

Part 1: Ranger – current operations

Contents[1]

1 List of papers grouped by Key Knowledge Need

Development of a contaminant pathways conceptual model for Ranger mine

R van Dam & P Bayliss

Background

A conceptual model of contaminant pathways from the operational phase of Ranger uranium mine is being developed. The early development of the model was reported on by Finlayson and Bayliss (2003) and van Dam et al (2004). The primary purpose of the conceptual model will be to place the off-site contaminant issues at Ranger in a risk management context. Moreover, the final product, as well as being used for formal risk assessment (see summary for ARRTC KKN 5.1.1), will serve as a communication tool for both scientists and traditional owners. The summary below focuses on progress towards the finalisation of the technical content of the model and an overview of the proposed involvement of, and communication with, traditional owners to complete the model.

Progress

To date, the development of the conceptual model has involved an internal technical expert panel approach to identify, and agree on, the relevant details within the following model elements:

- stressors (chemical, physico-chemical, radiological, biological)

and then for each stressor, its:

- sources
- transport mechanisms off-site
- affected environmental compartments
- receptor organisms
- routes of exposure
- types of effect
- measures of effect

Details within each of these elements have been compiled and constructed diagrammatically, as shown in figure 1. For each stressor transport pathway sub-model, the relevant linkages have been made that indicate how a stressor leaves the mine site, where in the environment it is distributed, what biota (including humans) could be exposed and affected, and what monitoring is in place, or needs to be in place, to detect effects.

As an example, the sub-model for inorganic toxicant transport via one of several specific surface water transport mechanisms is shown in figure 2. Amongst other pathways, inorganic toxicants can be transported off the mine site by surface water runoff and/or direct mine water discharges/overflows, and enter the nearby creeks. Depending on the nature of the toxicant, once in the creek it can partition into, and move between, various environmental compartments, most notably the water column, the sediment or the resident aquatic biota. Various biotic groups will be potentially exposed to the toxicant in these environmental compartments. For example, phytoplankton exposed directly from the water column, fish exposed directly from both the water column and from consuming prey that have taken-up and accumulated the toxicant, and benthic macroinvertebrates exposed directly from the sediment. In addition, people and other terrestrial animals can consume aquatic organisms that have taken-up and accumulated the toxicant. However, the extent to which the various exposure pathways are relevant and important in terms of resulting in adverse effects on receptor organisms depends on many biotic and abiotic factors (eg. relative contribution of the pathway to the total exposure of the receptor organism, sensitivity/tolerance of the receptor organism to the contaminant, environmental conditions that influence the bioavailability of the contaminant). To ensure that the Supervising Scientist can meet its primary objective of ensuring the protection of the people and the environment of the Alligator Rivers Region from the effects of uranium mining (termed as *assessment endpoints* in the conceptual model), various physico-chemical and biological indicators or *measurement endpoints* are assessed and monitored, as surrogates of the assessment endpoints. As can be seen in figure 2, the model indicates the relationship between the receptor organisms and the assessment endpoints (SSD objectives) and measurement endpoints (SSD monitoring and assessment programs).

Steps for completion

The following tasks will be undertaken in 2005–06 to complete the contaminant pathways conceptual model:

1 External technical stakeholder (ERA, EWLS, DBIRD) meeting to affirm and finalise technical aspects of the model;

2 Traditional Owner consultation: Other than risk assessment, one of the key functions of the conceptual model will be as a communication tool for outlining the types, pathways and relative risks of contaminants from Ranger. Suitability of the conceptual model as a communication tool for Traditional Owners will be assessed by incorporating their views and input through a workshop facilitated by the Aboriginal Communications Officer. Following the workshop an iterative process of consultation will be undertaken to ensure their input is correctly presented. It is anticipated that the final communication product for Traditional Owners will be presented in DVD format and a final graphical and narrative descriptions of the model.

When complete, the conceptual model will represent an iteration of previous models, having incorporated new knowledge and understanding of the relevant processes and issues. It will provide the framework for a quantitative comparison of risks (see summary for ARRTC KKN 5.1.1) and uncertainties for all stressor transport pathway sub-models. It will also enable historical and current activities and priorities to be evaluated, and future priorities to be determined. Further, it will act as a knowledge and communication management tool, within a risk management framework that links clearly to the ongoing management of mining operations.

References

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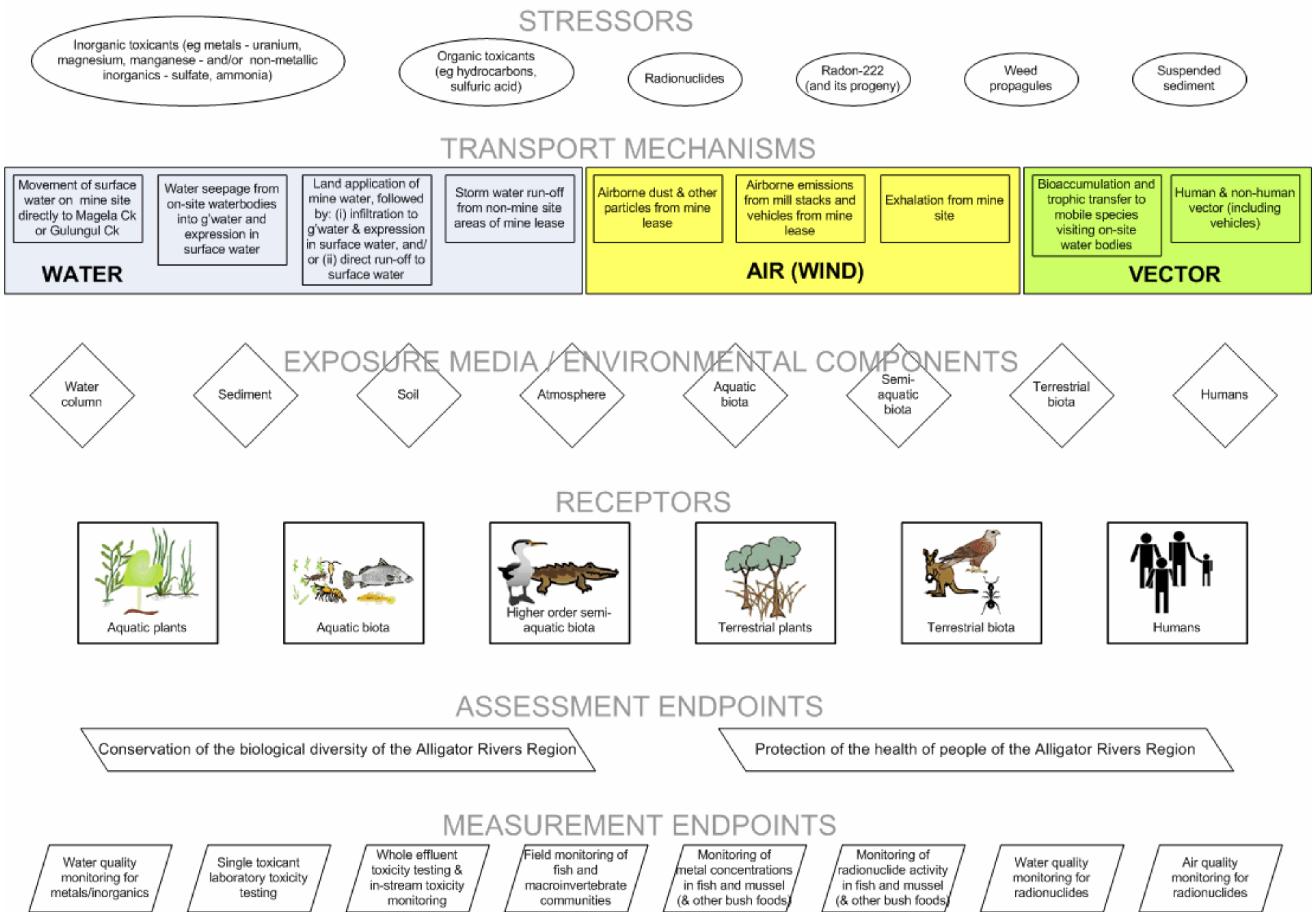

Figure 1 Basic elements of a contaminant pathways conceptual model for Ranger uranium mine

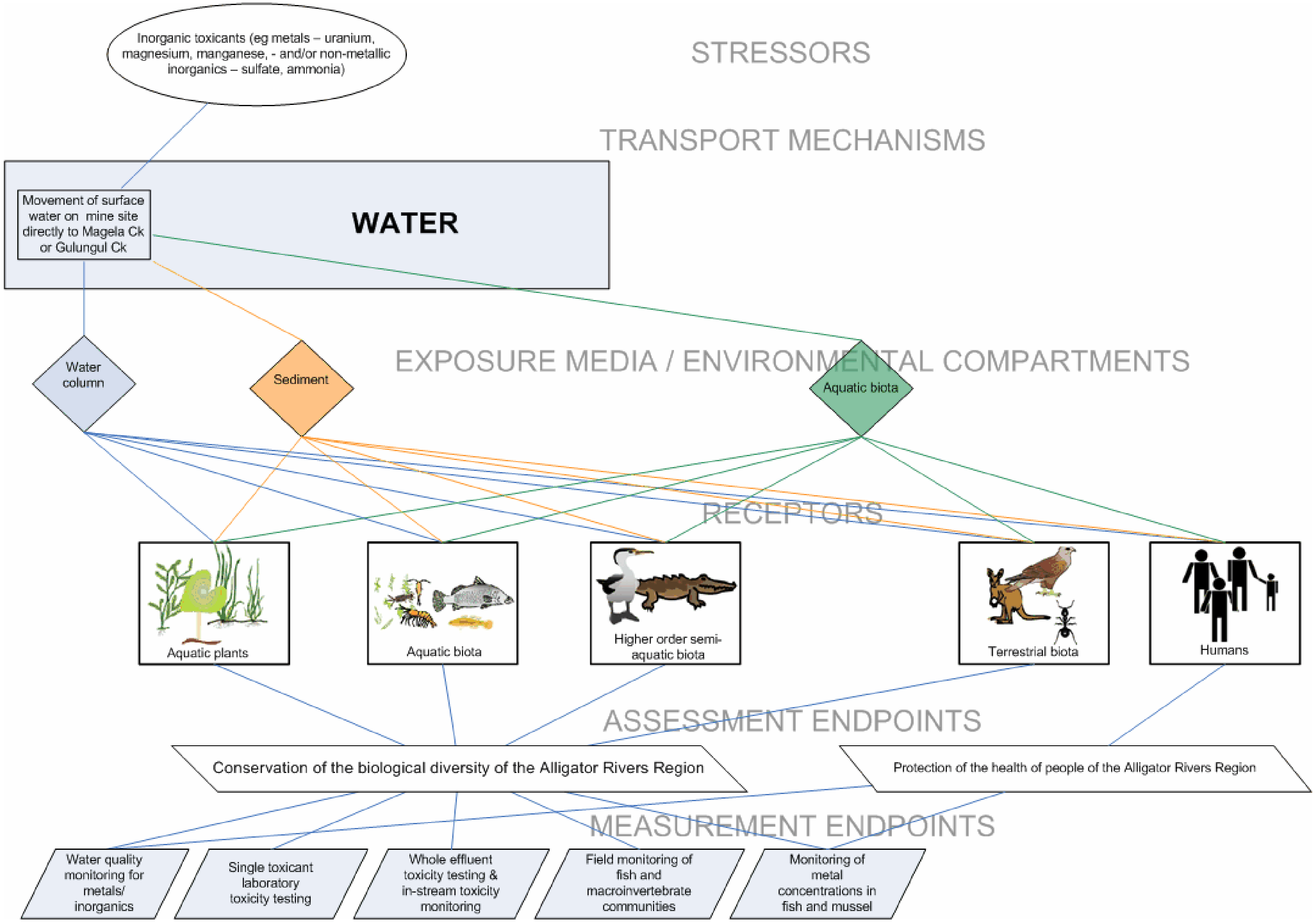

Figure 2 Conceptual model for transport of inorganic toxicants from Ranger uranium mine via a direct suface water to surface water pathway

Preliminary assessment of bioaccumulation and trophic transfer of key metals from Ranger mine

R van Dam, C Sauerland, K Turner, C Humphrey, B Ryan & A Bollhöfer

Background

Prior to the finalisation of the ARRTC Key Knowledge Needs (KKNs), a draft version of the KKN document (Draft 4.6.03) stated the following with respect to the uptake and trophic transfer of contaminants:

> ERISS has accumulated a considerable amount of ecotoxicological knowledge related to the effects of key contaminants on aquatic biota known to be present in the ARR. However, little of this information has been put into a management context, and has not been linked to the various biophysical pathways. For example, terrestrial environment & food sources have not been investigated. The possible transfer of contaminants such as uranium off site via the food chain should at least be assessed from a risk assessment perspective. What are possible pathways (e.g. waterbirds eating fish, sediment-dwelling invertebrates inhabiting RP1 and other close billabongs; terrestrial animals and birds eating plants and invertebrates inhabiting soil of land-application areas etc)?

Thus, in addition to the contaminant pathways conceptual model project summarised above, a project was initiated to review existing data to assess bioaccumulation and trophic transfer of metals associated with Ranger mine. The summary below focuses on the progress of this project during 2004–05 and presents a plan for its completion in 2005–06. The information summarised below was presented at the 8th International Conference on the Biogeochemistry of Trace Metals, in Adelaide, 3–7 April 2005 (van Dam et al 2005).

Progress and summary of findings to date

It should be noted that substantial bioaccumulation data for metals and radionuclides in aquatic and terrestrial biota have been collected over the past 20 years, albeit not necessarily as part of one program or a systematic series of programs. What was required for this project was a synthesis of the available data and an associated assessment of the ability to make conclusions about the ecological and human health risks of bioaccumulation and trophic transfer.

In planning the review and assessment, a 6 step process was developed:

1 Provide background on bioaccumulation and trophic transfer of metals and radionuclides;

2 Identify potential pathways and key metals for bioaccumulation and trophic transfer from mining at Ranger;

3 Collect and review available information (hard and electronic copy) from the ARR on concentrations/bioaccumulation/trophic transfer of key metals and radionuclides in aquatic (eg aquatic plants, invertebrates, fish), semi-aquatic (eg turtles, crocs, waterbirds) and terrestrial biota (eg lizards), and, if possible, relate to concentrations in the relevant environmental compartment(s) (eg water column, sediment, soil, vegetation/fruits);

4 Review national and international literature on bioaccumulation and trophic transfer (and subsequent effects) of metals and radionuclides identified from step 3 as being the most likely to bioaccumulate and/or biomagnify;

5 Where possible, identify ecological risks (and associated uncertainties) to the ARR of adverse effects arising from bioaccumulation/trophic transfer of key metals and radionuclides through comparison of exposure (steps 2 and 3) and effects (step 4); and

6 Identify information/research gaps.

Progress was made on all of the above steps, although the project was not completed (see below). The following key transport pathways were identified through the related project on the contaminant pathways conceptual model (see above):

- Direct movement/release of surface water on the mine site/lease directly to Magela Creek or Gulungul Creek (includes catchment runoff and release of retention pond waters);
- Seepage of water from on-site water bodies into groundwater and expression in surface water;
- Spray and flood irrigation of mine water to land, with subsequent infiltration to groundwater and expression in groundwater; and
- Biological uptake in mobile species inhabiting or visiting on-site water bodies.

The first three pathways represent the movement of on-site water to off-site natural surface waters and, ultimately, relate to the potential for bioaccumulation and biomagnification in biota exposed to highly diluted, relatively low concentrations of metals and radionuclides in the water column, or sediments of depositional zones. The fourth pathway is unique and relates primarily to the exposure of biota to waters that are moderately to highly contaminated, and the associated potential for metals and radionuclides to be accumulated as well as biomagnified and transported off-site via a biotic vector.

Metals of potential concern were identified based on historical assessments (eg Brown et al 1985, Noller 1991) and more recent information on ore and waste rock characteristics and process reagents. Given the pathways described above, it was clear that the two distinct exposure scenarios to consider for metal bioaccumulation/trophic transfer are those in:

- *off-site waterbodies:* the highly diluted surface waters of Magela Creek; and
- *on-site waterbodies:* the moderately to highly contaminated surface waters of the on-site water bodies at Ranger.

Moreover, given the high dilution of waste waters released to Magela Creek, it was clear that fewer metals will be of concern in the off-site waterbodies than the on-site waterbodies. Therefore, the list of metals of concern was screened, using two criteria, to identify key metals for this review and assessment, as summarised in table 1.

In total, over 100 published articles related to metals in the environment of the ARR have been located. Of these, approximately half are related to metal and/or radionuclide concentrations in biota. It needs to be emphasised that the vast majority of the data are yet to be screened for quality and used for the assessment. Data presented here are restricted to two studies only, one being the only study that has addressed the issue of trophic transfer of metals in on-site waterbodies (Batterham & Overall 1999) and another that addresses bioaccumulation of radionuclides and metals in the freshwater mussel (*Velesunio angasi*) downstream of Ranger (Ryan et al 2005).

Table 1 Criteria for selecting key metals

Exposure scenario	Criteria for selection of key metals	Key metals
Exposure in ***on-site*** waterbodies (ie highly contaminated surface waters)	'Metals of concern' that have a moderate to high potential to bioaccumulate [1]	arsenic, barium, cadmium, chromium, cobalt, copper, lead, manganese, mercury, selenium, silver, strontium, uranium, vanadium, zinc
Exposure in ***off-site*** downstream waterbodies (ie surface waters with highly diluted metal concentrations)	Key metals for *on-site* exposure scenario, for which concentrations in Magela Creek downstream of Ranger are elevated relative to concentrations upstream of Ranger [2]	manganese, uranium, zinc

[1] *Information sources:* ATSDR Toxicological Profiles, IPCS Environmental Health Criteria + other specific references.

[2] *Statistics:* Paired t-tests (one-tailed; α=0.05) + percentile approach.

Batterham and Overall (1999) sampled and measured tissue metal concentrations in four trophic groups from Ranger waterbodies representing a gradient of contamination. The results for uranium are shown in figure 1. In summary, bioaccumulation was evident at lower trophic levels (eg plankton), but not at higher trophic levels (eg fish), and this result was consistent among all the metals measured (data not shown). A reduction in tissue metal concentration with increasing trophic status is generally regarded as an indication that biomagnification is not occurring. This is not unexpected as there is very little evidence in the literature that inorganic metals biomagnify (Chapman et al 2003, McGeer et al 2004, Suedel et al 1994). However, there are numerous limitations associated with the work of Batterham and Overall (1999), including the fact that various key trophic pathways were not assessed (eg transfer of metals from aquatic flora and/or fauna to waterbirds and/or mammals). These pathways are important as they represent potential pathways for contaminants to be transported off the mine site.

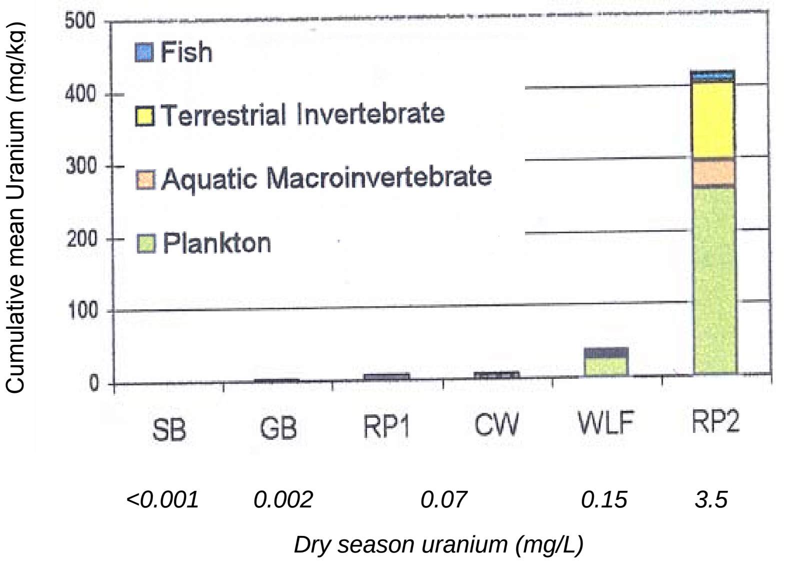

Figure 1 Cumulative mean uranium concentration (mg/kg) in four trophic groups sampled from five Ranger waterbodies (GB – Georgetown Billabong; RP1 – Retention Pond 1; CW – Corridor Creek wetlands; WLF – RP1 constructed wetland filter; RP2 – Retention Pond 2) and one Nourlangie billabong (SB – Sandy Billabong; reference site, unaffected by mining). Typical dry season surface water uranium concentrations (mg/L) for the waterbodies during the study are indicated in italics. From Batterham and Overall (1999).

Ryan et al (2005) reported radionuclide and metal concentrations in freshwater mussels collected from Mudginberri Billabong, downstream of Ranger, from 2000 to 2003, and Sandy

Billabong, in the nearby Nourlangie catchment, in 2002 and 2003. Notwithstanding a number of qualifications regarding the sampling methods and locations over the four year sampling period for Mudginberri Billabong (see Ryan et al 2005 for details), a summary of the data for uranium is shown in figure 2. For both 2002 and 2003, tissue uranium concentrations were higher in mussels from the 'exposed' (Mudginberri) site compared to mussels from the 'unexposed' (Sandy) site (two-sample T tests, $P < 0.05$), despite a limited water quality dataset revealing little difference in surface water uranium concentration between the two billabongs. However, the difference in mussel tissue uranium concentration between the two sites is relatively small (ie ~1.5×), and, given the low temporal resolution (ie. two years comparative data only), it is not possible to be conclusive until the many additional datasets are evaluated. For example, it is worth noting that the uranium concentrations in Mudginberri Billabong mussels reported by Ryan et al (2005) were similar, if not slightly lower, than those reported 15 to 20 years earlier by Johnston et al (1987). Thus, even if future monitoring data affirm the apparent difference between the two sites, there will be a need to establish whether the difference relates to a catchment signal or a mining signal. In contrast to the results for uranium, tissue manganese and zinc concentrations in mussels from Mudginberri Billabong were not significantly higher than in mussels from Sandy Billabong (data not shown).

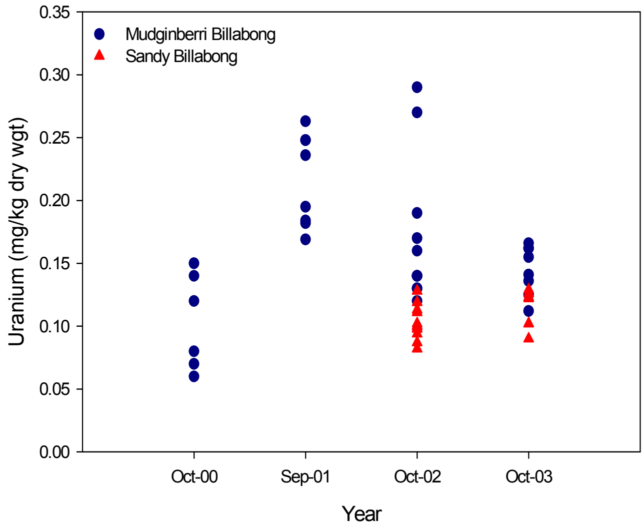

Figure 2 Tissue uranium concentrations (mg/kg dry weight) in freshwater mussels (*Velesunio angasi*) collected from Mudginberri Billabong from 2000 to 2003 and Sandy Billabong in 2002 and 2003. In general, each data point represents the uranium concentration for a composite sample of mussels from the same age (year) group. Data from Ryan et al (2005).

Preliminary conclusions

Although only a limited amount of data have been evaluated to date, a few preliminary conclusions can be made, as follows:

- The Ranger waterbodies trophic pathways study by Batterham and Overall (1999) and the majority of international literature on the issue of trophic transfer and biomagnification of metals, strongly indicate that, while trophic transfer of metals in aquatic environments does occur, biomagnification does not. Consequently, the transport of metals off site via a food chain pathway is unlikely to be a major transport mechanism.

- However, some data gaps exist for species at higher trophic levels, particularly herbivorous and piscivorous waterbirds;
- Although many data still remain to be analysed in relation to metals bioaccumulation in freshwater mussels (and other biota), there are indications of slightly elevated uranium concentrations in mussels downstream of Ranger relative to reference site mussels. However, there are uncertainties in the data, and there is a need for greater temporal resolution as well as an ability to establish whether any difference between the sites represents a catchment signal or a mining signal. In contrast, there is no evidence of elevated manganese or zinc in mussels downstream of Ranger.

Steps for completion

Due to high staff workloads and the need to better integrate the various related projects and/or reviews currently underway, this project has been subsumed into a broader program of works relating to the measurement and/or monitoring of radionuclides and metals in flora and fauna. The issue of trophic transfer, and off-site transport, of metals from on-site waterbodies will be addressed as part of the ongoing review and collation of data for the traditional bush foods project. This project has already developed and populated an Excel template and GIS for the multiple datasets for radionuclides (see summary for ARRTC KKN 2.5.1). The extent to which this is also done for key stable metals will depend on the level of priority assigned to the task as determined by the preliminary findings and discussions with ARRTC. At the very least, existing data of appropriate quality should be collated, with particular focus on data from on-site waterbodies. Further, in order to best answer the trophic transfer question raised by ARRTC (see *Background* to this project), the following steps could be undertaken:

1 Define/agree on 2–3 key trophic pathways for off-site transport, and within these, identify key trophic groups/species (animal and plant) to focus on species-specific data searching.

2 For the key trophic groups/species and key metals, collate and analyse existing data on tissue metal concentrations in biota on the mine area versus away from the mine (ie. exposed v reference), including consideration of associated water, sediment and/or soil concentrations.

3 Relate the above information to existing national/international literature on trophic transfer/ biomagnification of key metals (NB – much of this literature has already been summarised) including, if relevant, studies linking metal body burdens to adverse effects (more data searching is required here, although, overall, there is a general paucity of information on this topic).

4 Summarise site-specific ecological information on key species' feeding behaviour, feeding ground visitation, numbers potentially exposed/affected, etc.

5 Integrate the above information in a risk assessment context, including: ecological risks of individual key trophic pathways; relative risks of the key trophic pathways; and risks of the trophic pathways relative to other pathways (eg surface water). The latter is more an issue that will be addressed as the contaminant pathways conceptual model is populated.

The issue of bioaccumulation downstream of Ranger will be addressed as part of the ongoing (and currently under review) bioaccumulation monitoring program (see summary for ARRTC KKN 1.3.1).

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Influence of calcium on the ecotoxicity of magnesium: Implications for water quality trigger values

R van Dam, A Hogan, C McCullough[1], C Humphrey, S Nou[2] & M Douglas[3]

Background

Magnesium sulfate ($MgSO_4$), the dominant surface water contaminant associated with the ERA Ranger Mine, is generally considered to be of very low toxicity, Aquatic surveys around Ranger (O'Connor et al 1995) showed correlations between changes in macroinvertebrate community structure and increasing $MgSO_4$, prompting a full ecotoxicological investigation, including: identification of the dominant toxic ion; assessment of Mg toxicity in extremely soft local creek water (laboratory and field); and the influence of calcium (Ca) on Mg toxicity (laboratory), see Supervising Scientist 2002, 2003. Here, we present research quantifying the influence of Ca on Mg toxicity and the implications of this on a site-specific water quality trigger value for Mg. Although the majority of the work presented here was carried out during 2004–05, some additional data has been included to provide better context.

Progress and summary of findings to date

The three species (of six assessed) most sensitive to Mg in local Magela Creek water (duckweed, *Lemna aequinoctialis*; snail, *Amerianna cumingi*; green hydra, *Hydra viridissima*) were used to quantify the influence of Ca on Mg toxicity. The test species were exposed to a constant Mg concentration, being the concentration known to result in a 50% inhibition of response (eg population growth, reproduction) relative to unexposed (control) organisms, at increasing concentrations of Ca. Test results show that as Ca increases (ie as Mg:Ca decreases), Mg toxicity decreases for all three species (fig 1). For *Hydra* and *Lemna*, a full recovery was observed, whilst an approximate 80% recovery was observed for *Amerianna*. The differences in the extent of recovery between species is possibly due to different mechanisms of toxicity of Mg. Using the relationships from figure 1, a Mg:Ca ratio of 9:1 (ie that being the approximate 10% effect level for both *Hydra* and *Lemna*) was considered the best approximation of a ratio that minimises the likelihood of unacceptable Mg toxicity.

To complete the research, the toxicity of Mg was again fully characterised using six local freshwater species, but this time the Ca concentration was also manipulated such that the Mg:Ca ratio was maintained at the 'safe' ratio of 9:1. The summary results, compared to those obtained for Mg in the presence of only Magela Creek background Ca concentration (~0.2 mg/L), are shown in table 1. The IC_{15} values[4] presented represent maximum concentrations of Mg above which effects to the organisms might be considered ecologically unacceptable. For all species, Mg toxicity was markedly lower at the Mg:Ca ratio of 9:1.

[1] Edith Cowan University, Joondalup, WA

[2] Formerly SSD; now Kakadu National Park, Parks Australia North, Department of the Environment & Heritage

[3] Charles Darwin University, Darwin, NT.

[4] See table 1 footnote.

However, the extent to which toxicity was reduced varied between species. For example, the cladoceran and snail were approximately only 2× less sensitive to Mg in the presence of Ca, whilst the gudgeon was well over 200× less sensitive. These differences in relative sensitivity are possibly due to different physiologies of the test species and different mechanisms of toxicity of Mg.

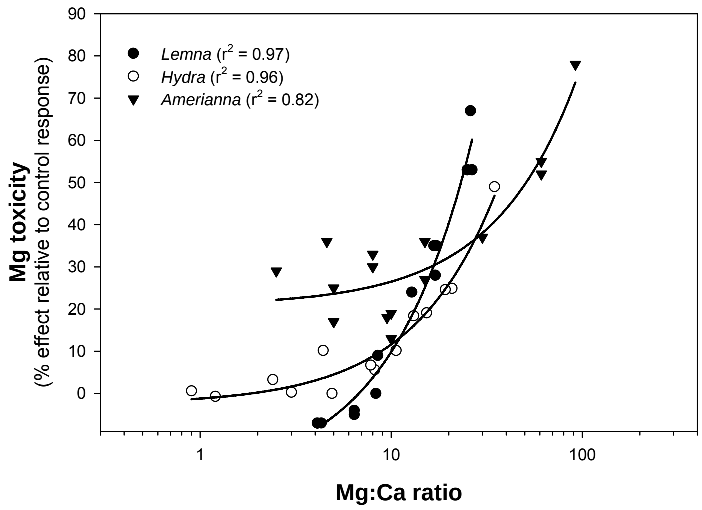

Figure 1 Effect of Ca (expressed as Mg:Ca ratio) on the toxicity of Mg to three species, when Mg concentration was held constant at the IC_{50} concentration (ie. 5 mg/L for *Lemna*, 10 mg/L for *Hydra*, 18 mg/L for *Amerianna*)

Table 1 Toxicity of Mg to six tropical freshwater species (a) without additional Ca and (b) with Ca added to maintain a Mg:Ca ratio of 9:1

		Mg toxicity (mg/L; expressed as IC_{15} values)[1]	
Species	**Endpoint (acute/chronic)**	**A. Without additional Ca[2]**	**B. At Mg:Ca ratio of 9:1[3]**
Green alga (*Chlorella* sp.)	72-h cell division rate (chronic)	93	1830[4]
Duckweed (*Lemna aequinoctialis*)	96-h plant growth (chronic)	2.2	155
Cladoceran (*Moindaphnia macleayi*)	3-brood reproduction (chronic)	24	37[4]
Snail (*Amerianna cumingi*)	96-h reproduction (chronic)	4.1	10
Green hydra (*Hydra viridissima*)	96-h population growth (chronic)	4.2	329
Purple-spotted gudgeon (*Mogurnda mogurnda*)	96-h survival (acute)	16[5]	4300[4,5]

1 IC_{15}: The concentration resulting in a 15% inhibition of response (eg reproduction) relative to unexposed (ie. control) organisms.

2 Except where noted, data for each species represent geometric means of IC_{15} values from 3 independent toxicity tests.

3 Except where noted, data for each species represent geometric means of IC_{15} values from 2 independent toxicity tests .

4 Data for each species represent values from 1 toxicity test. These data should be considered as interim only.

5 Data for *M. mogurnda* represent LC_5 values; the LC_5 being the concentration resulting in 5% mortality relative to unexposed (ie. control) organisms. This more conservative value is required because the endpoint for this test represents an acute, lethal response.

Using the BurrliOZ[5] species sensitivity distribution approach, a site-specific water quality trigger value for Mg in Magela Creek was derived. Given that Magela Creek lies largely within the World Heritage and Ramsar listed Kakadu National Park, a high level of protection is required. The derived water quality trigger value for Mg will protect at least 99% of species. Based on the Burr Type III distribution (black fitted line in figure 2), the concentration of Mg that should protect at least 99% of species is approximately 1 mg/L when Ca concentration is maintained at Magela Creek background Ca concentration, and approximately 4 mg/L[6] when Ca concentration is manipulated to maintain the Mg:Ca ratio at 9:1.

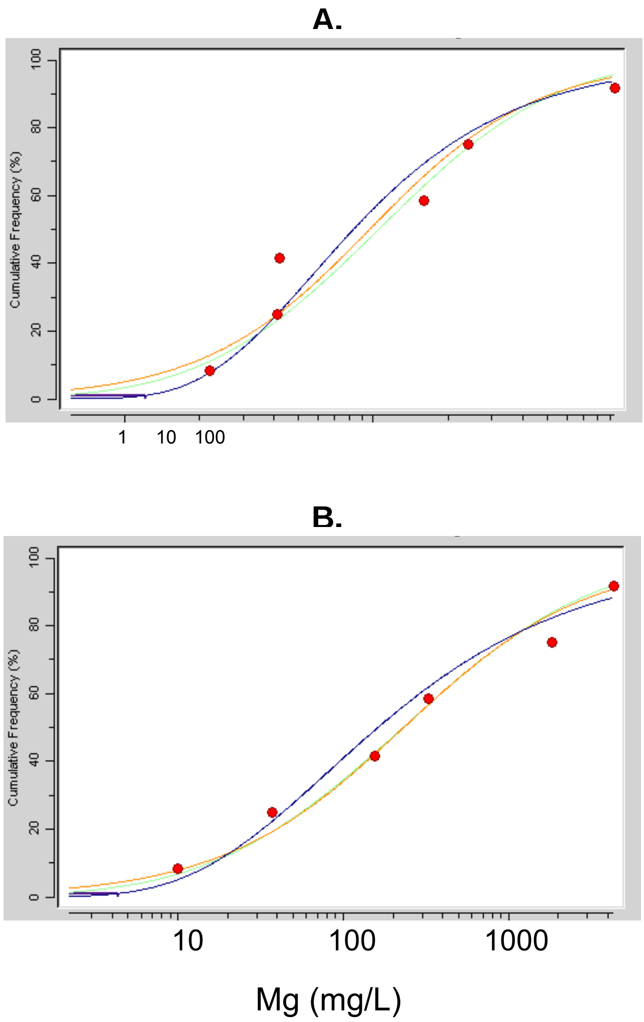

Figure 2 BurrliOZ species sensitivity distributions for Mg toxicity at (A) natural Magela Creek backgound Ca concentration (ie. ~0.2 mg/L) and (B) a constant Mg:Ca ratio of 9:1 (Note the different *x* axis scales). Data points represent the IC_{15} toxicity values for each species (see table 1) and are plotted as the cumulative frequency. The Burr Type III distribution is represented by the black fitted curve, and is the distribution used to calculate the trigger values for Mg (as recommended by ANZECC & ARMCANZ 2000).

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5 BurrliOZ is a statistical software package that was specifically developed for the ANZECC & ARMCANZ (2000) Water Quality Guidelines to calculate water quality trigger values.

6 This must be considered an interim value because the full toxicity data set is yet to be completed for several species (see table 1).

The above four-fold difference in the two trigger values is of significance to the management of discharged waste water at Ranger, because the discharged waters contain elevated Ca as well as elevated Mg. Thus, the Ca in Ranger waste waters is able to provide a protective function against potential Mg toxicity, and this needs to be taken into account when developing a site-specific trigger value. Therefore, if the Mg:Ca ratio in Magela Creek downstream of Ranger is maintained at or below 9:1, Mg concentrations of up to 4 mg/L should present very low risk to the local aquatic biota. To illustrate the low risk to aquatic biota to date, based on actual water quality data, figure 3 shows cumulative frequency distributions for Mg and the Mg:Ca ratio as measured at the monitoring point downstream of Ranger, from 1985 to 2005. The Mg trigger value has been exceeded only approximately 0.5% of the time, whilst the Mg:Ca ratio of 9:1 has not been exceeded. Thus, these data, although not finalised, indicate there is negligible risk to the aquatic biota of Magela Creek from Mg in surface water as a result of current mining operations. Had the Mg trigger value of ~1 mg/L, which does not account for the ameliorative effect of Ca on Mg toxicity, been applied, the risk to aquatic biota would have been significantly overestimated. Although yet to be finalised, the process of deriving the trigger value will almost certainly require consideration of both the Mg concentration and the Mg:Ca ratio.

Steps for completion

All that remains to complete this project is to finish several more Mg toxicity tests at the Mg:Ca ratio of 9:1. At the time of preparation of this summary, an additional test needed to be completed for *Chlorella* sp., *M. macleayi* and *M. mogurnda*. Following this, the Mg toxicity, and associated, research will be submitted for publication as one or two papers in an international peer-reviewed journal. Also, the results were presented at the bi-annual conference of the Australasian Society for Ecotoxicology, in Melbourne, 23–28 September 2005 (van Dam et al 2005).

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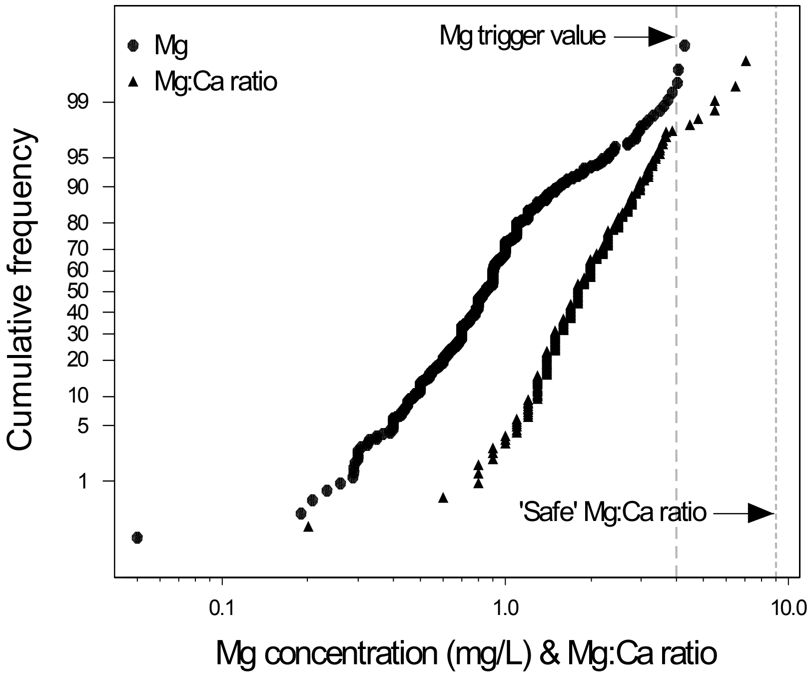

Figure 3 Cumulative probability distributions for Mg concentration and Mg:Ca ratio in Magela Creek downstream of Ranger, from 1985–2005. The vertical broken lines represent, from left to right, the Mg trigger value of 4 mg/L (when the Mg:Ca ratio is maintained at or below 9:1) and the 'safe' Mg:Ca ratio of 9:1

Chronic toxicity of uranium to the tropical duckweed, *Lemna aequinoctialis*

R van Dam, S Nou[1] & A Hogan

Background

As uranium is one of the primary toxicants associated with the water released from Ranger, a receiving water Trigger Value (TV) has been derived specifically for Magela Creek according to the ANZECC and ARMCANZ Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ 2000). The site-specific TV of 6 µg/L is classified as being of 'high reliability' due to the use for its derivation of chronic toxicity data from five local species representing four taxonomic groups (see Hogan et al 2005). Although not detailed here, there are several reasons to support the need to further strengthen the uranium chronic toxicity dataset. However, the worth of generating uranium chronic toxicity data for additional species must be weighed against the normally large effort and cost required to develop new toxicity tests. The recent refinement of a growth inhibition test using the tropical duckweed, *Lemna aequinoctialis,* and the development of a reproduction test using the pulmonate gastropod, *Amerianna cumingi*, provided an opportunity to increase the chronic toxicity dataset for uranium with minimal additional developmental effort and cost. When data for these species are added to the existing suite of species that have been assessed, uranium toxicity data will exist for seven species from six taxonomic groups, a marked improvement on the current dataset. The site-specific uranium toxicity tests using the *L. aequinoctialis* growth inhibition test are summarised in this report.

Aims

The aims of this study were to (i) determine the minimum concentrations of nutrients (nitrate and phosphate) required to be added to natural Magela Creek water (NMCW) to ensure acceptable growth of *L. aequinoctialis* in control treatments, and, using the revised protocol, (ii) assess the chronic toxicity of uranium to *L. aequinoctialis* in NMCW.

Methods

The *L. aequinoctialis* 96 h growth inhibition toxicity test procedure is described in full by Riethmuller et al (2003). For this study, two series of experiments were carried out.

Nutrient optimisation tests: Two experiments were undertaken to determine the minimum concentrations of nitrate (NO_3) and phosphate (PO_4) that need to be added to NMCW in order to obtain acceptable *L. aequinoctialis* growth (ie four-fold increase in initial frond numbers after 96 h). The nutrients were added to each treatment at a NO_3:PO_4 ratio of 10:1 (N:P ≈7:1) at the following concentrations (NO_3/PO_4):

Test 1: 0/0, 0.1/0.01, 0.3/0.03, 1/0.1, 3/0.3, 10/1, 30/3 and 100/10 mg/L

Test 2: 0/0, 0.3/0.03, 1/0.1, 3/0.3, 10/1 and 30/3 mg/L

[1] Kakadu National Park, Parks Australia North, Department of the Environment and Heritage

One-way analysis of variance (ANOVA) followed by a Fisher's pairwise comparison was used to identify significant differences between treatments ($\alpha = 0.05$).

Uranium chronic toxicity tests: One rangefinder and three definitive experiments were undertaken to characterise the effect of uranium exposure on the growth of *L. aequinoctialis* in NMCW. Concentrations of uranium assessed in each of the three definitive tests were:

Test 1: 0, 50, 100, 250, 500, 750, 1000 µg/L

Test 2: 0, 250, 500, 750, 1000, 1500, 2000, 3000 µg/L

Test 3: 0, 50, 100, 250, 500, 750, 1000, 1500 µg/L

Analysis of covariance (ANCOVA) was used to determine whether the concentration-response relationships for the three definitive uranium toxicity tests were significantly different ($\alpha = 0.05$), and to determine the validity of pooling the datasets for further statistical analysis. If valid, the data were pooled and a one-tailed Bonferoni T-test was used to determine the Lowest-Observed-Effect-Concentration (LOEC) and the No-Observed-Effect-Concentration (NOEC) of uranium ($\alpha = 0.05$). In addition, non-linear regression was used to characterise the concentration-response relationship and to calculate inhibition concentrations (IC_x) of uranium corresponding to a 10, 25 and 50% inhibition of response compared to the control response (ie. IC_{10}, IC_{25} and IC_{50}).

Results and discussion

Nutrient optimisation tests: The minimum NO_3/PO_4 combination at which plant growth exceeded the control acceptability criterion of a four-fold increase in frond number was 3 mg/L NO_3 and 0.3 mg/L PO_4 (equivalent to 0.7 mg/L N and 0.1 mg/L P) (figure 1). Plant growth at this NO_3/PO_4 combination was not significantly different to growth at any of the higher concentrations ($P > 0.05$). At lower concentrations, plant growth was significantly lower ($P < 0.05$), and well below the minimum acceptable control criterion. These nutrient concentrations were selected for addition to NMCW for the uranium chronic toxicity tests.

Uranium chronic toxicity tests: ANCOVA indicated that the concentration–response relationships for each of the three definitive tests were not significantly different (F = 0.895, df = 2, $P = 0.430$), and as such, the data were pooled for further analysis and interpretation. The resultant concentration–response relationship is shown in figure 2. Based on this dataset, the LOEC and NOEC were 247 µg/L and 216 µg/L, respectively. At the LOEC concentration, there was an approximate 20% reduction in plant growth relative to controls. Plant growth decreased to around 30–40% of the control up to a concentration of around 700 µg/L, but plateaued thereafter. The concentration–response relationship was best described by a 4 parameter logistic distribution ($r^2 = 0.97$, n = 19, $P < 0.001$; see figure 2). Using this model, the IC_{10}, IC_{25} and IC_{50} (95% confidence intervals) were calculated to be 187 (130–228) µg/L, 291 (256–325) µg/L and 504 (449–572) µg/L, respectively.

L. aequinoctialis exhibited similar sensitivity to uranium as the green hydra, *Hydra viridissima* (NOEC = 183 µg/L; Hogan et al 2005). It is noteworthy that plant growth, albeit around 3 fold lower than in controls, was still observed at uranium concentrations in excess of 1000 µg/L. In comparison, complete inhibition of population growth (and death) of *H. viridissima* occurs at only 250–300 µg uranium/L (ARRRI 1988). Thus, *L. aequinoctialis* is able to maintain some growth at concentrations of uranium that are lethal to other species that have been assessed. A similar ability was reported for *L. aequinoctialis* exposed to the herbicide tebuthiuron, in this instance in comparison to the response of the green alga, *Chlorella* sp. (van Dam et al 2004).

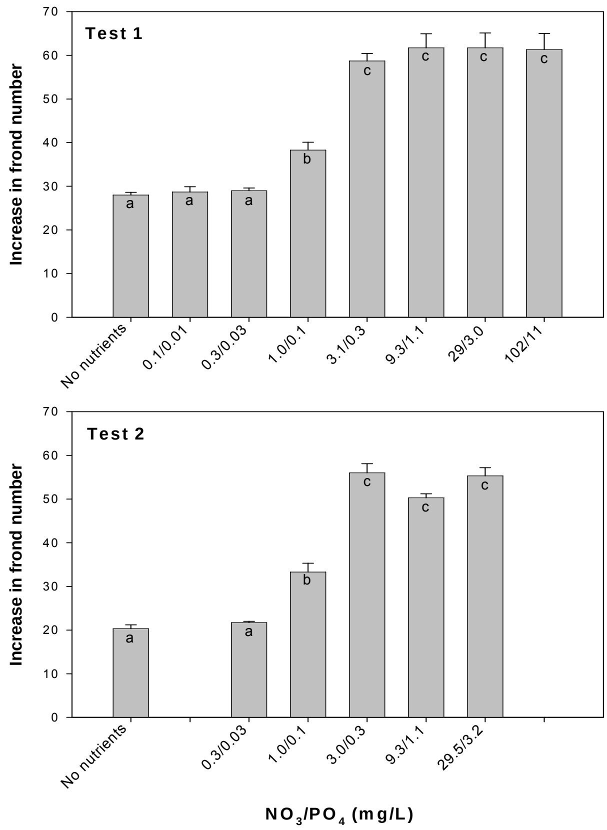

Figure 1 Effect of various combinations of nitrate (NO_3) and phosphate (PO_4) concentrations (measured) on growth of *L. aequinoctialis* over 96 h. Results for each treatment are expressed as the mean (±SEM) of three replicates. Treatments with a letter in common are not significantly different from each other (P>0.05).0

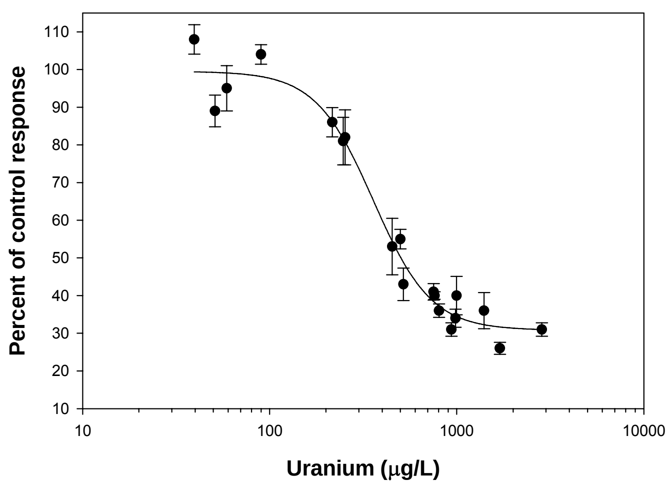

Figure 2 Response of *L. aequinoctialis* growth to uranium (measured) based on the pooled dataset and relative to the pooled control response of 55.4 ± 1.4 fronds (mean ± SEM; n = 9). The fitted curve represents a 4 parameter logistic model (r^2 = 0.97, n = 19, P < 0.0001).

If the *L. aequinoctialis* NOEC of 216 µg/L (or IC_{10} of 187 µg/L) is added to the existing uranium chronic toxicity dataset, the resultant 99% protection trigger value for uranium increases from 6 µg/L to around 9 µg/L (based on a log-logistic distribution). Not surprisingly, given the small sample size of six, the uncertainty remains high, with the 95% confidence interval being around 1–90 µg/L. A revised trigger value will not be formally published until the uranium toxicity experiments for the snail, *A. cumingi*, have been completed.

Steps for completion

An internal report of the *L. aequinoctialis* testing is almost complete. This research, and that to be completed in 2005-06 for the snail, will be combined and submitted for publication in an international peer-reviewed journal, most likely in 2006.

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Development of a reference toxicity testing program for *Chlorella* sp. and *Hydra viridissima*

A Hogan, R van Dam & S Nou[1]

Background

The ***eriss*** ecotoxicology laboratory generally has good procedures in place to ensure quality of results. However, one key gap in the laboratory's QA/QC program is a regular reference toxicity testing program for the routine toxicity testing species. This gap was identified by a review of the ecotoxicology research program by van Dam (2004) and also by Dr Jenny Stauber at ARRTC's 14th meeting. Consequently, it was agreed by ARRTC that a formal project be initiated to develop a reference toxicity testing program. This project was initiated in 2004, with the focus being on the green alga, *Chlorella* sp, and the green hydra, *Hydra viridissima*, and is proposed to be continued in 2005. The reference toxicant being used is uranium. This summary outlines the progress made during 2004–05.

Progress

Two reference toxicity tests (using synthetic Magela Creek water – SMCW) for *Chlorella* sp and three for *H. viridissima* were completed in 2004–05, as scheduled. Given the existence of four and three reference toxicity test results for *H. viridissima* and *Chlorella* sp, respectively, the 04–05 testing enabled the construction of reference toxicant control charts for each species (given that a minimum of five test results are required in order to construct a control chart; Environment Canada 1990). The relevant uranium toxicity data are shown in table 1. The controls charts are shown in figure 1.

For *Chlorella* sp, the running mean IC_{50} is currently around 65 µg U/L. To date, no test results have deviated beyond the *warning limits* (ie two standard deviations above or below the running mean), indicating a consistent experimental technique and response of the test species to uranium over time. However, the last two reference toxicity tests were invalid due to unacceptably low control growth. This response has not been observed in recent *Chlorella* sp. tests run in natural Magela Creek natural water (NMCW). Measures being undertaken to investigate the cause of the response include: sending the algal culture to CSIRO (Sydney) for treatment to return it to an axenic state; sending samples of SMCW stock solutions for chemical analysis, and renewing nutrient stock solutions. The success of these measures will be known in September.

For *H. viridissima*, the running mean IC_{50} is currently around 103 µg U/L. To date, no test results have deviated beyond the warning limits, indicating a consistent experimental technique and response of the test species to uranium over time.

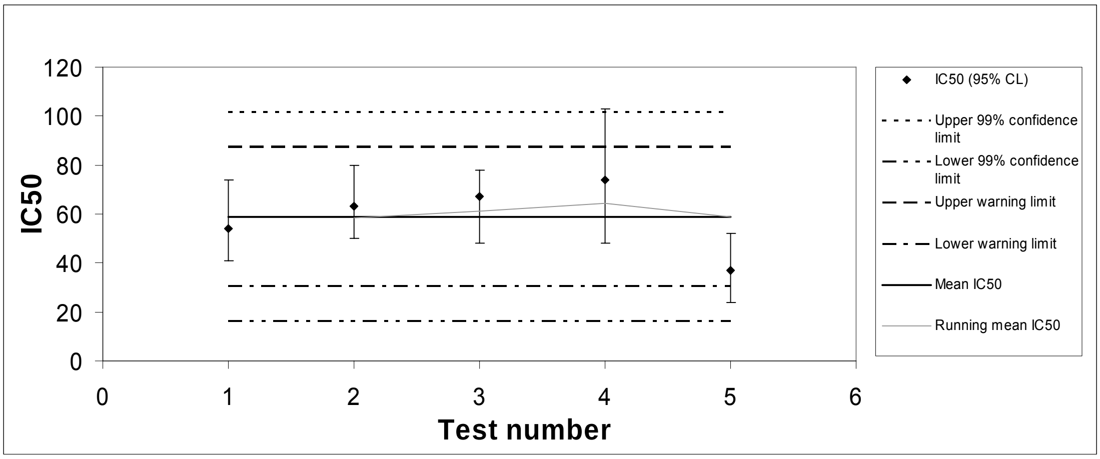
[1] Formerly SSD; now Kakadu National Park, Parks Australia North, Department of the Environment & Heritage

Table 1 Uranium reference toxicity test results for *chlorella* sp. and *hydra viridissima*

Species	Endpoint	Test No.	IC_{50} (µg/L)	Reference
Green alga (*Chlorella* sp)	72-h cell division rate	1	54 (41–74)[1]	Franklin et al (1998)
		2	63 (50–80)	Franklin et al (1998)
		3	67 (48–78)	Franklin et al (1998)
		4	74 (48–103)	Hogan et al (2005)
		5	37 (24–52)	This study
		6	Invalid test[2]	This study
		7	Invalid test[2]	This study
Green hydra (*Hydra viridissima*)	96-h population growth	1	133 (99–158)	Riethmuller et al (2000)
		2	108 (100–142)	Riethmuller et al (2000)
		3	117 (CL not calculable)	Riethmuller et al (2000)
		4	85 (68–93)	This study
		5	80 (67–94)	This study
		6	94 (78–113)	This study

1 Values in parentheses represent 95% confidence intervals.

2 Invalid *Chlorella* sp. tests were due to poor control growth. See main text for discussion and steps to rectify this issue.



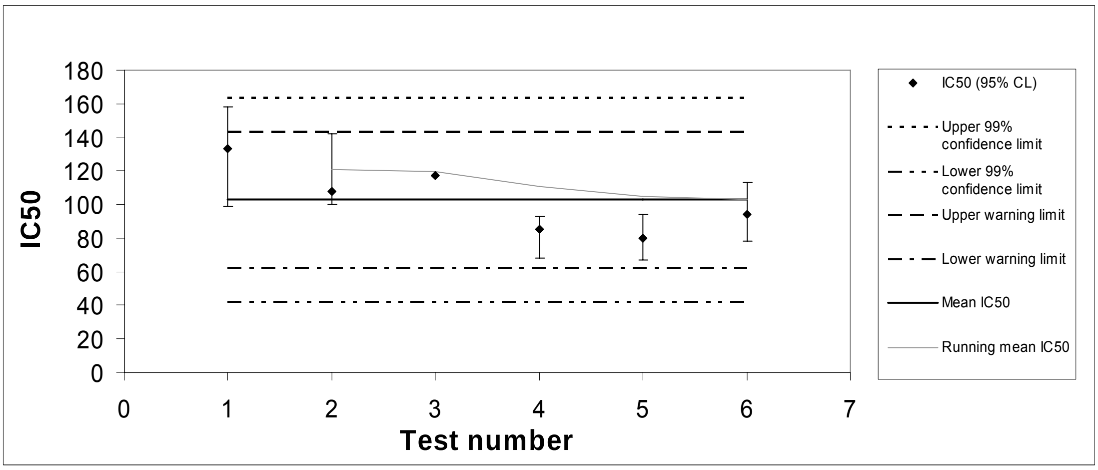


Figure 1 Control charts showing reference toxicity test data for (top) *Chlorella* sp and (bottom) *Hydra viridissima*

Steps for completion

The reference toxicity testing program is an ongoing program. Hence, it is expected that approximately four reference toxicity tests for both the above two species will again be completed in 2005–06. Further, 2005–06 will focus on the establishment of reference toxicity testing programs for the duckweed, *Lemna aequinoctialis*, and the purple-spotted gudgeon, *Mogurnda mogurnda*.

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Revision of the ecotoxicology laboratory manual

A Hogan

Background

A comprehensive manual of all routine laboratory procedures has been a central reference document in the ecotoxicology laboratory since the late 1980s. While being designed as a dynamic document that undergoes regular minor updates, the relocation of the laboratory to Darwin required more significant amendments. This was also recognised as an opportunity to review the order, style and format of the manual to make it more user-friendly and up to date.

Progress on the laboratory manual revision was slow for the first two years after the relocation, with staff only managing to spend a small amount of time on it between projects. The benefits of being able to devote solid blocks of time to this work was recognised and the revision was made a formal project on the 2004–2005 workplan.

Progress

Major revisions of all the original chapters have been completed. A chapter on the new aquaculture water system is at a final draft stage. A new chapter on *Lemna* maintenance and small sections on the new methods for taking water chemistry samples and care and maintenance of the incubators still need to be written. Some graphics still need to be added and pasted in and more photographs throughout the document would be useful. The order of chapters is still to be assessed to improve the flow of the document and final formatting will need to be undertaken.

Steps for completion

Laboratory staff will complete the water chemistry, incubator and aquaculture water system sections and insert final graphics during October. All ecotoxicology staff will then meet to identify any information gaps and to decide on the final order of chapters. Laboratory staff will then check for continuity between chapters and standardise the formatting throughout the document (possibly with assistance from our publications officer).

Atmospheric radiological monitoring in the vicinity of Ranger and Jabiluka

A Bollhöfer, D Elphick[1] & SA Atkins

Introduction

The International Commission on Radiation Protection (ICRP 1991) recommends that the annual dose received from practices such as uranium mining and milling should not exceed 1 milli Sievert (mSv) per year. The ICRP furthermore states in paragraph 6.2.1 of Publication 77 (ICRP 1997) that 'To allow for exposures to multiple sources, the maximum value of the constraint used in the optimisation of protection for a single source should be less than 1 mSv in a year. A value of no more than about 0.3 mSv in a year would be appropriate.' This dose is on top of the radiation dose received naturally, which averages to approximately 2 mSv per year in Australia, but typically varies between 1–10 mSv per year (UNSCEAR 2000).

Ranger is the main potential anthropogenic source of radiation exposure to the community in the Alligator Rivers Region. During the operational phase of a uranium mine there are two potential exposure pathways to the general public. The inhalation pathway, which is a result of dispersion of radionuclides from the mine site into the air, and the ingestion pathway, which is caused by the uptake of radionuclides into bushfoods from the Magela Creek system downstream of Ranger.

Methods

The Supervising Scientist monitors the two airborne pathways:

- Radioactivity trapped in or on dust (or long lived alpha activity, LLAA)
- Radon decay products (RDP).

Dust samples are collected monthly on 47 mm glass fibre filters for periods of 7–10 days, using a solar powered low volume dust sampler. After sample collection and allowing for the decay of short lived radionuclides (usually 5–7 days), LLAA is measured on a *Daybreak* gross alpha counter, calibrated using a certified ^{230}Th source.

Radon decay products are measured using a portable continuous radon and thoron working level monitoring system. This system pumps air through a filter and measures the subsequent decay of RDP collected on the filter with a built-in gross alpha detector counting all alpha energies above 1 MeV. The system is deployed for 24 continuous hours per month and data are downloaded from the unit's memory after a 3.5 hour decay analysis subsequent to the sampling cycle.

Results

The main areas of habitation are Jabiru, Mudginberri and Jabiru East, consequently monitoring focuses on those three population centres in the region. Airborne RDP and LLAA concentrations are measured monthly and the results are compared with Energy Resources of Australia's (ERA) quarterly and annual atmospheric monitoring results.

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[1] Formerly SSD; now Fisheries Division, NT Department of Primary Industry, Fisheries and Mines

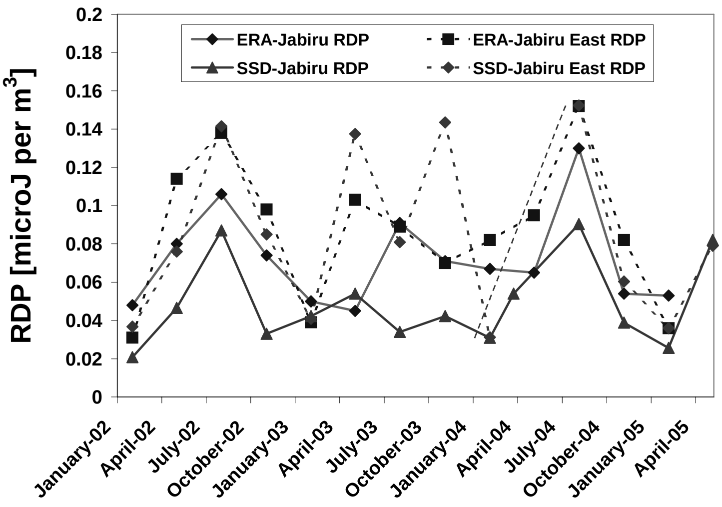

Figure 1 Radon decay product concentration measured by SSD and ERA in Jabiru and Jabiru East from 2002 to 2005

Figure 1 shows Jabiru and Jabiru East RDP data and a comparison with ERA data from January 2002 to April 2005. Differences in sampling time and location are most likely the cause of the differences in RDP concentrations observed at Jabiru, with ERA values being slightly higher than values measured by ***eriss***. The annual exposure due to the inhalation of radioactivity trapped in or on dust for people working in Jabiru East and living in Jabiru has been shown to be trivial and is less than 1% of the public dose limit (Bollhöfer et al 2005).

Table 1 shows the average annual doses received from the inhalation of RDP calculated from ***eriss*** and ERA (ERA, 2005) data at Jabiru. This is assuming an occupancy of 8760 hrs (1 year) and a dose conversion factor for the public of 0.0011mSv per $\mu J \cdot h/m^3$. Mine derived annual doses from the inhalation of radon progeny are shown as well, as calculated by ERA using a wind correlation model developed by ***eriss***, which correlates wind direction with airborne radon decay product concentration.

Table 1 Average annual RDP concentration measured by ***eriss*** and ERA (*italics*) at Jabiru East and Jabiru and doses received from the inhalation of RDP at Jabiru

		2002	2003	2004
RDP concentration [$\mu J/m^3$]	Jabiru East	0.085; *0.095*	0.101; *0.075*	0.095; *0.103*
	Jabiru	0.047; *0.077*	0.043; *0.065*	0.063; *0.079*
Total annual dose [mSv] Jabiru		0.45; *0.74*	0.41; *0.63*	0.61; *0.76*
Mine derived dose [mSv] at Jabiru		*0.03*	*0.011*	*0.014*

Although there were no activities reported at the Jabiluka mine site, the population group that may in theory receive a radiation dose due to future activities at Jabiluka is the 60 or so inhabitants of Mudginberri, a small community approximately 10 km south of Jabiluka. At Four Gates Rd radon station, a few kilometres west of Mudginberri, the Supervising Scientist has a permanent atmospheric research and monitoring station. RDP and LLAA concentrations are measured there on a monthly basis. In addition, radon gas is continuously measured at the station with radon data being recorded every 30 minutes.

Figure 2 shows airborne RDP and LLAA concentrations measured at Four Gates Rd radon station by ***eriss***. Concentrations are very small and comparable with natural background levels (UNSCEAR 1993). The average airborne radionuclide concentrations measured in 2004 would translate into an annual total effective dose, including natural background, of 0.46 mSv from RDP and 0.013 mSv from LLAA. Only a small fraction of these doses would be due to mine derived radionuclides.

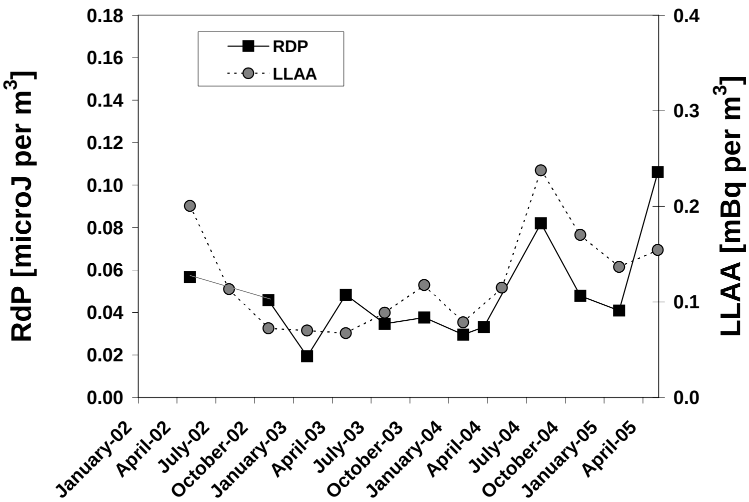

Figure 2 Radon decay product (RDP) and long lived alpha activity (LLAA) concentrations measured at ***eriss***'s Mudginberri Four Gates Rd radon station

References

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ICRP 1997. *Radiological protection policy for the disposal of radioactive waste*. Publication 77 of the International Commission on Radiological Protection. Pergamon Press, Oxford.

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Monitoring of radionuclides in groundwater at Ranger

B Ryan

Introduction

The aim of the Ranger groundwater program is to investigate the dispersion of contaminants through the groundwater pathway, both from a monitoring and hydrogeological modelling perspective.

Aquifers, both shallow and deep, and sources of contaminants need to be characterised, both geochemically and hydrogeologically, to enable the prediction of the dispersion of these contaminants. The monitoring program will also have to be continued during and following the rehabilitation of the mine to assess the success of the rehabilitation and the integrity of the pits as tailings repositories.

Progress to date

RUM bore water samples were collected by Department of Business, Industry and Resource Development for ***eriss*** in 2004 and aliquots prepared for radioisotope analysis. ICPMS-OES analysis of all archived groundwater samples were completed by Charles Darwin University in 2005 for barium, calcium, iron, sulphur, sodium, potassium, magnesium, manganese, vanadium, uranium and strontium.

Uranium isotope and radium analyses via alpha spectrometry of archived samples began in late 2004 and are not yet complete. During the 2004/05 financial year emphasis was given on the Nabarlek groundwater samples that had been collected and archived from 1996–2004.

Analyses and interpretation of the long-term groundwater data for uranium isotopes and radium will be undertaken in 2005–06 after all samples have been analysed, with particular attention being placed on assessing groundwater movement and any sources of contamination.

Radon concentrations in air in the Alligator Rivers Region

A Bollhöfer & P Martin[1]

Introduction

The radon network in the Alligator Rivers Region (ARR) was designed to provide detailed time-series radon concentration and meteorological data at various locations within the ARR over a time frame of several years:

- to provide information on the influence of past and present uranium mining and milling activities on radon concentrations in air in the ARR;
- to establish a baseline database to assist in assessment of any future mining activities;
- to provide datasets useful in assessing the effects of various factors on radon transport in the atmosphere. In particular to calibrate and verify radon transport models.

Four radon stations were used earlier in this project, with three stations placed throughout the ARR and on the Ranger mine lease, respectively, collecting data for periods of one year. One station is collecting data permanently at Four Gates Road radon station in the vicinity of Mudginberri as a control and monitoring site. The radon monitor at this site has now been collecting data for more than five years.

Methods

The sampling equipment used is described in detail in Tims (2001), Bollhöfer et al (2004) and Martin et al (2004). Briefly, air is drawn through a delay line of ~15 litres at a flow rate of approximately 5 litres per minute to remove thoron and then passes through a class P2 particulate filter to remove radon and thoron decay products. It then enters the tank with a volume of 100 litres where radon decays and radon progeny are circulated through and collected on a second filter mounted approximately 7 mm from a ZnS coated light guide, attached to a photomultiplier (PM) tube. The PM tube detects the light pulses generated in the scintillating ZnS coating by the α-particles emitted by the radon progeny. Pulses are fed into a discriminator and then directly into a data logger. Data are read into the long-term memory of a data logger every 30 minutes. The logger also records the internal tank pressure, the flow rate, the internal and external blower fan currents, the PM tube voltage, the internal battery voltages and the temperature. Data loggers are download approximately every two months.

Results

The Mudginberri Four Gates Road radon station radon dataset has been updated up to January 2005. A comprehensive QA/QC on the dataset to allow journal publication, is being conducted. A paper on the radon network in the ARR (Martin et al 2004) and an internal report on Nabarlek radon concentrations (Bollhöfer et al 2004) have been published.

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1 Formerly SSD; now Agency's Laboratories Seibersdorf, IAEA, A-1400, Vienna, Austria.

In figure 1 the daily averages of radon concentration measured at the Mudginberri Four Gates Rd radon station are plotted versus the date throughout the last 5 years, together with a weekly running average to the data. The data show the typical seasonal variations with higher radon concentrations measured during the dry season and lower values during the wet. The long-term average radon concentration at Mudginberri Four Gates Road radon station is 10 $Bq \cdot m^{-3}$, which is a value typical for outdoor environmental radon concentrations (UNSCEAR 2000).

Figure 1 highlights the variation occurring in airborne radon concentration caused by meteorological conditions. These variations may explain discrepancies between ERA and ***eriss***'s radon progeny monitoring data at Jabiru (East), which are occasionally observed as radon progeny monitoring is performed one day per month only, at different days of the month. With our dataset, maximum day-to-day differences in radon concentration have been estimated to be more than 25 $Bq \cdot m^{-3}$. This results in a maximum difference in average daily doses from the inhalation of radon progeny at Mudginberri of up to 2 μSv.

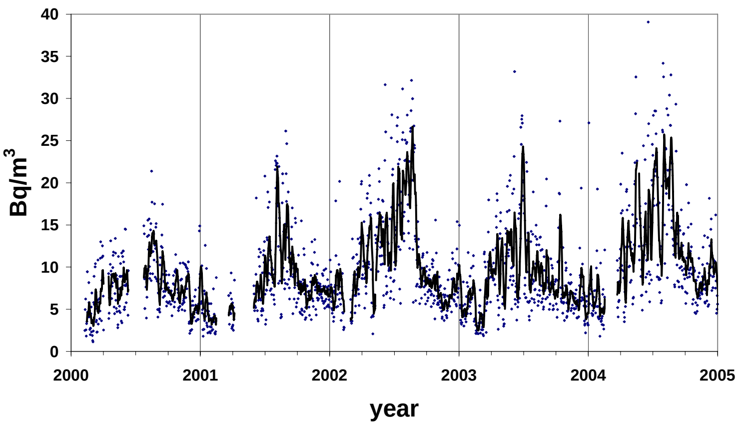

Figure 1 Daily averages of airborne radon concentration and weekly running average (solid line) measured at the Mudginberri Four Gates Road radon station plotted versus the date

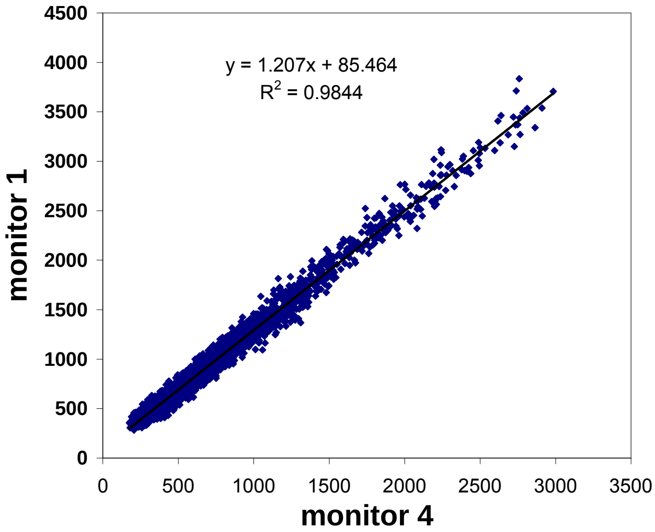

Figure 2 Net counts per 30 minutes of monitor 1 plotted against monitor 4

This year, an intercomparison between radon monitors 1 and 4 at Mudginberri Four Gates Road radon station was run for three consecutive months, from 17 January 2005 to 27 April 2005. Monitor 1 has been calibrated against a known radon concentration earlier in 2002 in ARPANSA's radon chamber in Melbourne (Bollhöfer et al 2004). The comparison shows that monitor 1 is about 20% more efficient than monitor 4, in agreement with calibration constants determined earlier in the laboratory using a Pylon radon source. These constants amounted to 0.018 ± 0.001 (monitor 1) and 0.020 ± 0.003 (monitor 4) Bq/m^3 per cts/30 min, respectively (Bollhöfer et al 2004). Monitor 1 has been used for cross calibration of the instruments since the ARPANSA calibration.

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Martin P, Tims S, Ryan B & Bollhöfer A 2004. A radon and meteorological measurement network for the Alligator Rivers Region, Australia. *Journal of Environmental Radioactivity* 76, 35–49.Tims S 2001. Operation and calibration of the ***eriss*** radon detectors. Internal Report 359, Supervising Scientist, Darwin. Unpublished paper.

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Introduction to SSD's stream monitoring program for Ranger, 2004–05

C Humphrey

Based upon its research program, SSD has implemented an integrated chemical, physical and biological control regime to ensure protection of the aquatic ecosystems of the Alligator Rivers Region from the operation of mines in the region. Since 2001, routine monitoring and ecotoxicity programs have been employed for environmental assessment of aquatic ecosystems.

The techniques and 'indicators' used in the monitoring program satisfy two important needs of environmental protection: (i) the early detection of potential significant effects to avoid ecologically important impacts; and (ii) information on the ecological importance of any likely impact (biodiversity assessment). Monitoring techniques adopted by SSD that meet these requirements are:

(i) Early detection of short or longer-term changes

- *Water chemistry* – physical and chemical indicators, including pH, electrical conductivity, suspended solids, uranium, magnesium, manganese and sulfate (weekly sampling during the wet season) and radium (fortnightly);
- *Creekside monitoring* of reproduction in freshwater snails and survival of fish fry (four-day tests conducted at fortnightly intervals during the wet season);
- *Bioaccumulation* – concentrations of chemicals (including radionuclides) in the tissues of freshwater mussels and fish at strategic locations downstream to detect far-field effects including those arising from any potential deposition of mine wastes in sediments (mussels sampled every late-dry season, fish sampled biannually in the late dry season).

(ii) Assessment of biodiversity

- *Benthic macroinvertebrate communities* at stream sites (sampled at the end of each wet season); and
- *Fish communities in billabongs* (sampled at the end of each wet season).

Bioaccumulation studies are currently under review and progress is reported separately in this report (Sauerland et al 2006). Results for water chemistry, creekside monitoring, macroinvertebrate (Magela and Gulungul creek sites only) and fish community studies conducted during the 2004–05 wet and early dry seasons, and macroinvertebrate studies carried out in 2004 are reported in the ensuing papers of this SSR.

Reference

Sauerland C, Ryan B, Humphrey C & Jones DR 2006. Review of the bioaccumulation monitoring program. In ***eriss** research summary 2004–2005*. eds Evans KG, Rovis-Hermann J, Webb A & Jones DR, Supervising Scientist Report 189, Supervising Scientist, Darwin NT, 60–62.

Chemical and physical monitoring of surface waters in Magela and Gulungul Creeks

M Iles

Magela Creek

The first water chemistry samples for the Supervising Scientist's 2004–05 wet season surface water monitoring program were collected from the Magela Creek downstream statutory compliance point, gauging station 009, on 21 December 2004, one day after the commencement of flow past the site. Weekly spot-sampling continued throughout the wet season with the last of the routine monitoring samples collected on 25 May 2005, the week before flow past the downstream compliance point ceased.

All indicators remained within limits/guidelines[1] throughout the 2004–05 wet season. The measured values are indicative of the pattern of improved quality seen in the past three wet seasons, exemplified in the uranium results of figure 1.

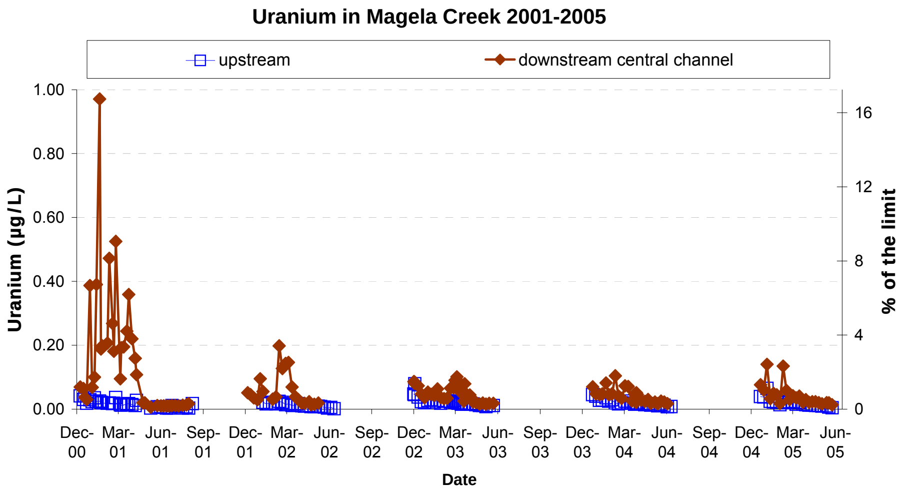

Figure 1 Uranium concentrations in Magela Creek since the 2000–01 wet season (SSD data)

The upstream and downstream key water quality data from both the SSD and ERA programs are summarised in table 1 with uranium concentrations shown in figure 2.

There appears to be good agreement between the datasets. Uranium, magnesium and sulfate wet season median concentrations from both datasets were higher downstream of the mine but the concentrations were very low and not of environmental concern. For the season, uranium was less than 3% of the limit and mostly less than 1% (figure 2). Electrical conductivity (EC), whose guideline value provides a management control for the magnesium and sulfate concentrations, was also slightly higher downstream but compared to the guideline value the difference was small. The manganese, pH, and turbidity medians are similar at both sites for each dataset.

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[1] The terms 'limit', 'guideline' and 'objective' are defined in the Supervising Scientist Annual Report for 2004–05

The water quality objectives set to protect the aquatic ecosystems downstream of the mine (provided in the Supervising Scientist annual report for 2004–05) were achieved during the 2004–05 wet season. Available biological monitoring data (ensuing papers) also indicate that the environment remained protected throughout the season.

Table 1 Summary of Magela Creek 2004–05 wet season water quality upstream and downstream of Ranger

Parameter	Guideline or Limit	Organisation	Median Upstream	Median Downstream	Range Upstream	Range Downstream
pH	5.0 – 6.9	SSD	6.3	6.3	5.4 – 6.7	5.8 – 6.7
		ERA	6.1	6.2	5.7 – 6.5	5.8 – 6.4
EC (μS/cm)	43	SSD	13	17	5.9 – 17	7.3 – 23
		ERA	12	14	7.9 – 18	8.4 – 19
Turbidity (NTU)	26	SSD	2.2	2.6	0.9 – 15	0.9 – 12
		ERA	2.	3.	<1 – 25	<1 – 5
Sulfate‡ (mg/L)	Limited by EC	SSD	0.2	0.7	0.1 – 0.3	0.2 – 1.8
		ERA	0.2	1.0	<0.1 – 0.8	0.4 – 3.2
Magnesium‡ (mg/L)	Limited by EC	SSD	0.5	0.8	0.2 – 0.8	0.3 – 1.0
		ERA	0.6	0.9	0.4 – 0.8	0.4 – 1.3
Manganese‡ (μg/L)	26	SSD	5.0	5.3	3.3 – 8	3.0 – 22
		ERA	6.0	5.7	2.7 – 13	1.5 – 17
Uranium‡ (μg/L)	6	SSD	0.015	0.031	0.004 – 0.065	0.014 – 0.145
		ERA	0.015	0.035	<0.005 – 0.048	0.018 – 0.174

ERA data taken from the ERA Weekly Water Quality Report 5 July 2005;

‡ dissolved (<0.45 μm);

A compliance limit applies to uranium; management guidelines apply to all other parameters shown.

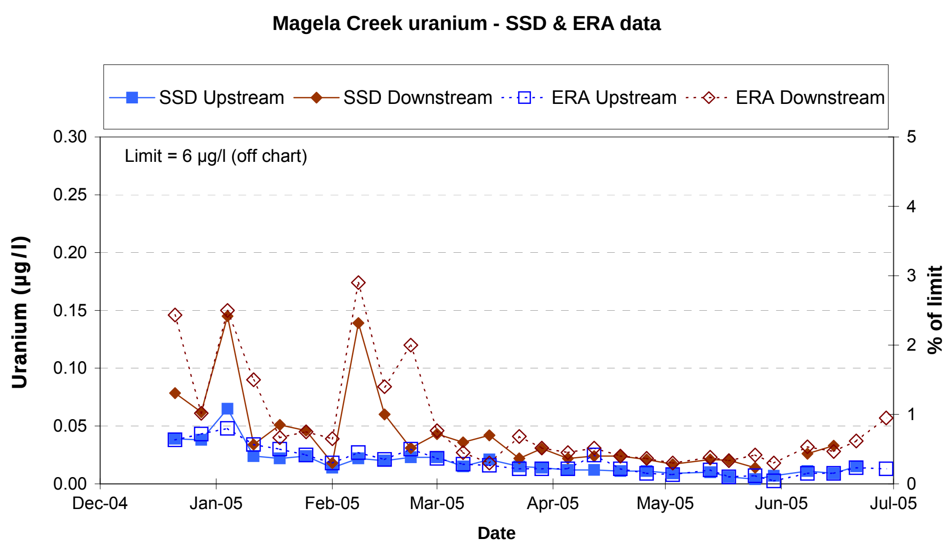


Figure 2 Uranium concentrations measured in Magela Creek by SSD and ERA during the 2004–05 wet season

Gulungul Creek

The first water chemistry samples for the Supervising Scientist's 2004–05 wet season surface water monitoring program were collected from Gulungul Creek on 23 December 2004, the first day of flow in the creek for the wet season. Weekly spot-sampling continued throughout the season with the last of the routine monitoring samples collected on 8 June 2005, during the week in which flow at the downstream site ceased.

The overall water quality and seasonal trends were comparable to those seen in previous years. This is demonstrated by the uranium concentrations shown in figure 3.

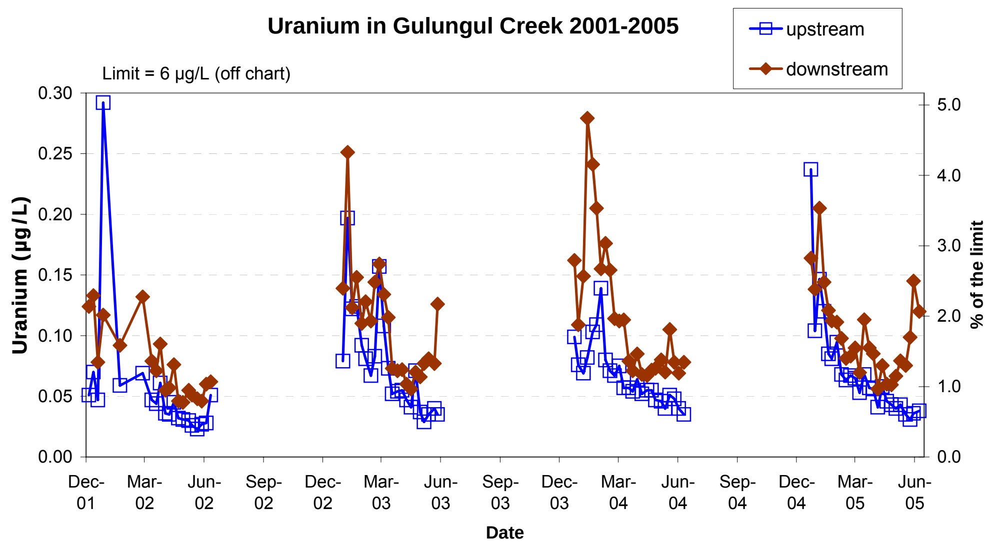


Figure 3 Uranium concentrations in Gulungul Creek since the 2000–01 wet season (SSD data)

The upstream and downstream key water quality data from both the SSD and ERA programs are summarised in table 2 with uranium concentrations shown in figure 4. There appears to be good agreement between the two datasets. Small differences could be attributable to different sampling times.

Table 2 Summary of Gulunugul Creek 2004–05 wet season water quality upstream and downstream of Ranger

Parameter	Company	Median		Range	
		Upstream	Downstream	Upstream	Downstream
pH	SSD	6.6	6.6	5.7 – 6.9	5.8 – 6.9
	ERA	6.3	6.3	8.9 – 6.8	6.0 – 6.8
EC (µS/cm)	SSD	17	21	9.0 – 26	9.4 – 28
	ERA	14	18	10 – 21	13 – 23
Turbidity	SSD	1.4	1.8	<0.5 – 4.0	0.6 – 6.7
(NTU)	ERA	1.	2.	<1 – 20	<1 – 7
Sulfate‡	SSD	0.2	0.5	<0.1 – 0.9	0.1 – 1.4
(mg/L)	ERA	0.2	0.6	0.1 – 1.0	0.1 – 2.3
Magnesium‡	SSD	0.9	1.1	0.4 – 1.6	0.4 – 1.5
(mg/L)	ERA	1.0	1.2	0.7 – 1.6	0.8 – 1.4
Manganese‡	SSD	2.7	3.0	1.2 – 8.0	0.7 – 15
(µg/L)	ERA	2.1	3.0	1.1 – 9.5	0.8 – 7.8
Uranium‡ *	SSD	0.058	0.093	0.031 – 0.237	0.058 – 0.212
(µg/L)	ERA	0.069	0.110	0.034 – 0.253	0.063 – 0.249

‡ dissolved (<0.45 µm), * limit = 6 µg/L

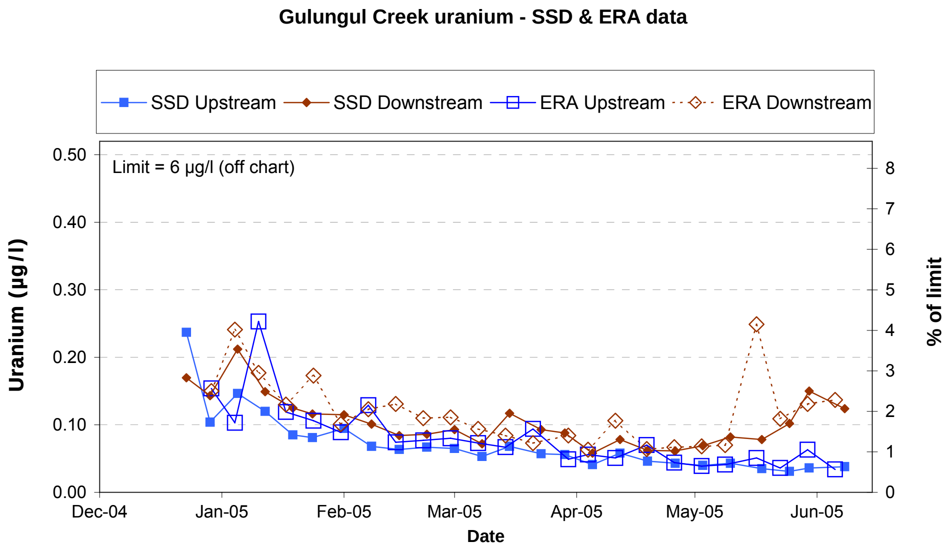


Figure 4 Uranium concentrations measured in Gulungul Creek by SSD and ERA during the 2004–05 wet season

Uranium concentrations in Gulungul Creek are naturally higher than those in Magela Creek (due to different geochemistry and hydrology influences in the respective catchments). Like Magela Creek, the concentrations at the Gulungul Creek downstream site are slightly higher than those at the upstream site. However, the uranium concentrations in Gulungul Creek were well below the limit throughout the season, with the concentration at both the upstream and downstream sites ranging between about 1% and 4% of the limit (figure 3).

Sulfate concentrations in Gulungul Creek were similar to those seen in previous years, with the downstream concentrations generally higher than those upstream but still well below levels of environmental concern[2]. The small difference in electrical conductivity (EC) between the upstream and downstream sites shows that the sulfate increase has little effect on the overall solute levels downstream of the mine. The EC trend at both upstream and downstream sites closely follows that of magnesium. Magnesium, manganese, pH and turbidity were similar at the upstream and downstream sites indicating that these variables are not, or only slightly, influenced by the mine.

[2] Toxicity tests on local *Hydra* and *Lemna* species demonstrated that SO_4 (as Na_2SO_4) exhibits very little, if any toxicity to these species below 200 mg L^{-1}.

Creekside monitoring in Magela Creek

C Humphrey, D Buckle & R Luxon

In this form of monitoring, effects of Ranger mine wastewater dispersion are evaluated using responses of aquatic animals held in tanks on the creek side and exposed to creek waters. The responses of two test species are measured over a four-day period:

- reproduction (egg production) in the freshwater snail, *Amerianna cumingi*, and
- survival of black-banded rainbowfish, *Melanotaenia nigrans*, larvae.

Animals are exposed to a continuous flow of water pumped from upstream of the minesite (control site) and from the creek just below gauging station GS8210009, some 5 km downstream of the mine. At each of the two sites, duplicate pumps in the creek feed water separately to: (i) in the case of snails, duplicate containers respectively, each container holding replicate (8) snail pairs; and (ii) in the case of fish, triplicate containers respectively, each container holding ten larval fish. At the end of each four-day test, the mean number of eggs per snail pair and mean number of fish surviving per replicate are noted and compared for each of the upstream and downstream sites. Specifically, when data from the downstream site are subtracted from those at the upstream site, a set of 'difference' values can be derived. These difference values may be compared statistically for different parts of the time-series. For example, 'difference' data for the wet season of interest may be compared with those from previous years; if they differ significantly, using a Student's *t* test, it may indicate a mine-related change. Since about 1996, creekside tests have been performed approximately every other week during the wet season. Tests usually commence in December and cease in early April, the period of significant creek flow in Magela Creek.

The results of the creekside trials are plotted as part of a continuous time series of actual and 'difference' data in figure 1A for snail egg production, and in figure 1B for larval fish survival. Descriptions of the sources of creekside data and data quality issues are provided in the Supervising Scientist's annual report for 2001–02 and website (http://www.deh.gov.au/ssd/monitoring/magela-bio.html).

Eight creekside tests were conducted in the 2004–05 wet season (late December 2004 to early April 2005.) Only five tests were conducted using larval fish, there being too few fish larvae available to conduct the fourth, sixth and seventh tests.

Amongst snail tests, egg production at upstream and downstream sites was similar across all tests conducted for the wet season (figure 1A). Using the data shown in figure 1A, 'difference' values for 2004–05 were compared with those from previous years. (The difference data shown and subsequently used in statistical analyses are those for valid tests only.) No significant difference was found ($P>0.05$).

The lack of fish larvae available in the fourth, sixth and seventh tests was a result of high mortality in the developing eggs held in broodstock waters at the Jabiru Field Station laboratories. Broodstock waters are taken from Magela Creek upstream of Ranger. Broodstock waters collected for these (failed) tests generally coincided with periods when flow in Magela Creek was unusually low. It is possible that during these periods, high water temperatures and insolation are conducive to the build up of micro-organisms that are harmful to fish larval development. This issue is being investigated, together with possible solutions to prevent future occurrences of such test failures.

Across all fish tests, larval fish survival at upstream and downstream sites was similar (figure 1B), apart from reduced survival at the upstream site relative to the downstream site during the third creekside test in particular (an observation commonly noted in previous years for this test species).

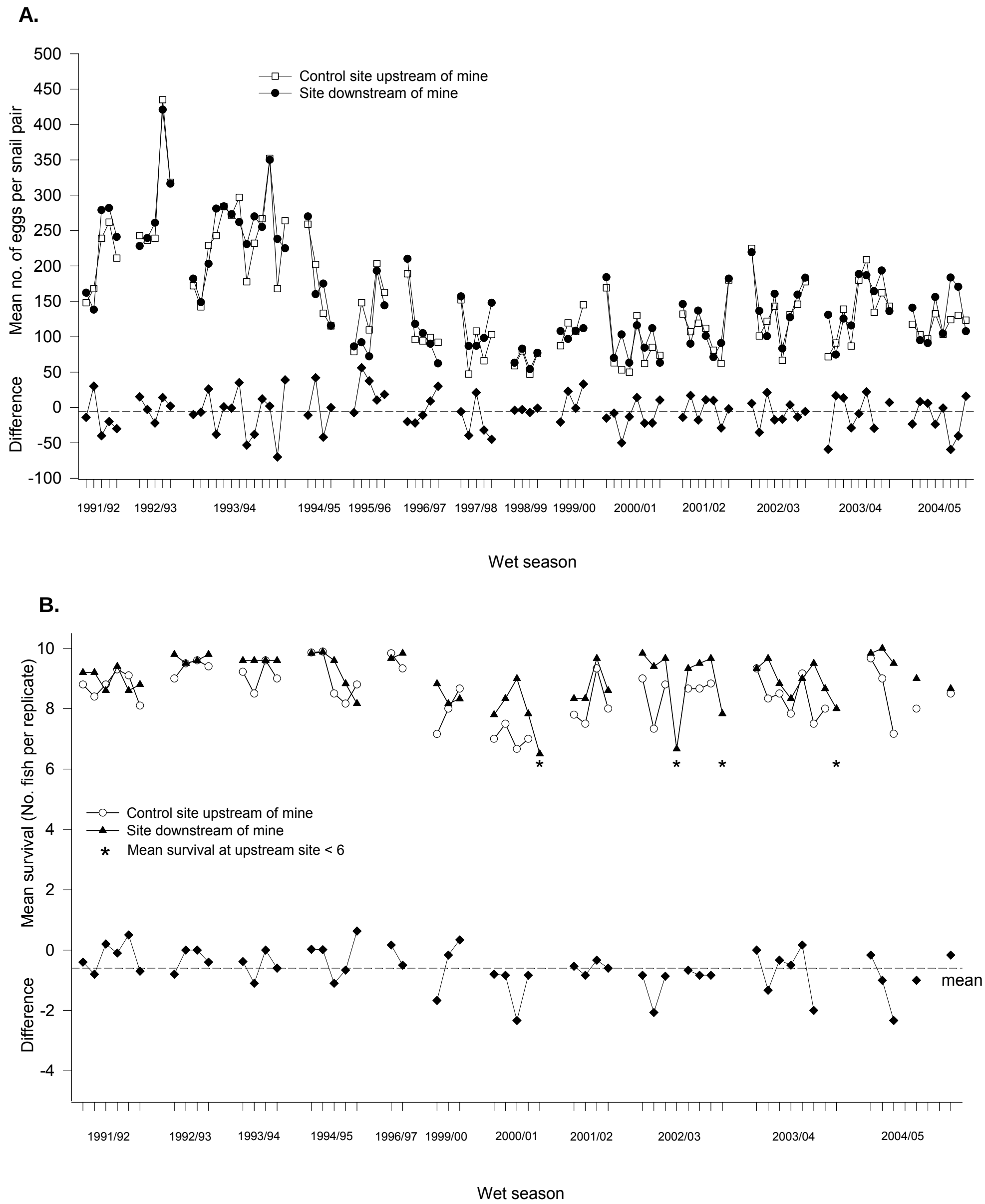


Figure 1 Creekside monitoring results for: A. freshwater snail egg production, and B. larval black-banded rainbowfish survival, for wet seasons between 1992 and 2005

In the Supervising Scientist annual report for 2003–2004, is was noted that fish survival 'difference' (upstream-downstream) data for the two periods 1991/92–96/97 and 1999/00–03/04 were significantly different from one another as a consequence of the reduced larval fish survival at the upstream control site in the period 1999/00–02/03. (Possible causes are discussed in the Supervising Scientist annual report for 2002–2003.)

With the inclusion of 2004/05 data, the same significant difference, 1991/92–96/97 versus 1999/00–03/04 (P=0.004), was observed. When 'difference' results for 2004/05 were compared separately with results for the two time periods (1991/92–96/97 and 1999/00–03/04), then:

- a significant difference was found in the comparison 1991/92–96/97 versus 2004/05 ($P<0.05$), but
- no significant difference was found in the comparison 1999/00–03/04 versus 2004/05 ($P>0.05$).

This result indicates that larval fish survival at the downstream relative to upstream (control) site in Magela Creek during 2004/05 was consistent with the same relative survival rates observed in the previous five wet seasons.

From the collective creekside results, it was concluded that there were no adverse effects of dispersed Ranger mine waste waters to Magela Creek on either of the creekside test species over the 2004–05 wet season.

Monitoring using macroinvertebrate community structure

C Humphrey, J Hanley, C Camilleri & A Cameron[1]

Macroinvertebrate communities have been sampled from a number of sites in Magela Creek at the end of significant wet season flows, each year from 1988 to the present. The design and methodology have been gradually refined over this period to meet the needs of cost efficiency and improved ability to confidently attribute any observed changes to mining impact. The most significant refinement that took place in the study occurred in 1994 when there was a reduction from ten sites sampled in Magela Creek to just three, as well as commencement of sampling at sites in three additional control streams. Since 1994, there have also been three changes to sampling and sample processing methods.

The refined (1994) design for this macroinvertebrate study was based on the principle of gathering macroinvertebrate samples from sites in Magela Creek upstream and downstream of Ranger, and also from similar paired upstream and downstream sites in three adjacent 'control' streams that are generally unaffected by any mining activity. In recent years, it has become evident that Gulungul Creek has been receiving some small quantities of mine contaminants from Ranger. Given its doubtful role as a true control stream, it is more appropriate now to consider this stream in the same category as Magela Creek, that is, 'exposed'. The design of this study, therefore, is now a balanced one comprising two 'exposed' streams and two control streams.

Samples were collected from each site at the end of each wet season (between April and May). For each sampling occasion and for each pair of sites for a particular stream, a dissimilarity index is calculated. This index is a measure of the extent to which macroinvertebrate communities of the two sites differ from one another. A value of 'zero' indicates identical macroinvertebrate communities while a value of 'one' indicates totally dissimilar communities, sharing no common taxa.

Research elsewhere in the Alligator Rivers Region (eg Faith et al 1995) has shown significantly 'higher' dissimilarity values for locations upstream and downstream of point sources of disturbance compared with values recorded in both the pre-disturbance, baseline period and in undisturbed control streams; the higher dissimilarity is a consequence of the 'altered' (disturbed) macroinvertebrate community structure at (the) site(s) downstream of such point sources.

Analysis of the full macroinvertebrate data set from 1988 to 2004, and data from the paired sites in the two 'exposed' streams, Magela and Gulungul creeks for 2005, has been completed and results are shown in figure 1. This figure plots the paired-site dissimilarity values using family-level (log-transformed) data, for the two Magela catchment streams and two Nourlangie catchment (control) streams.

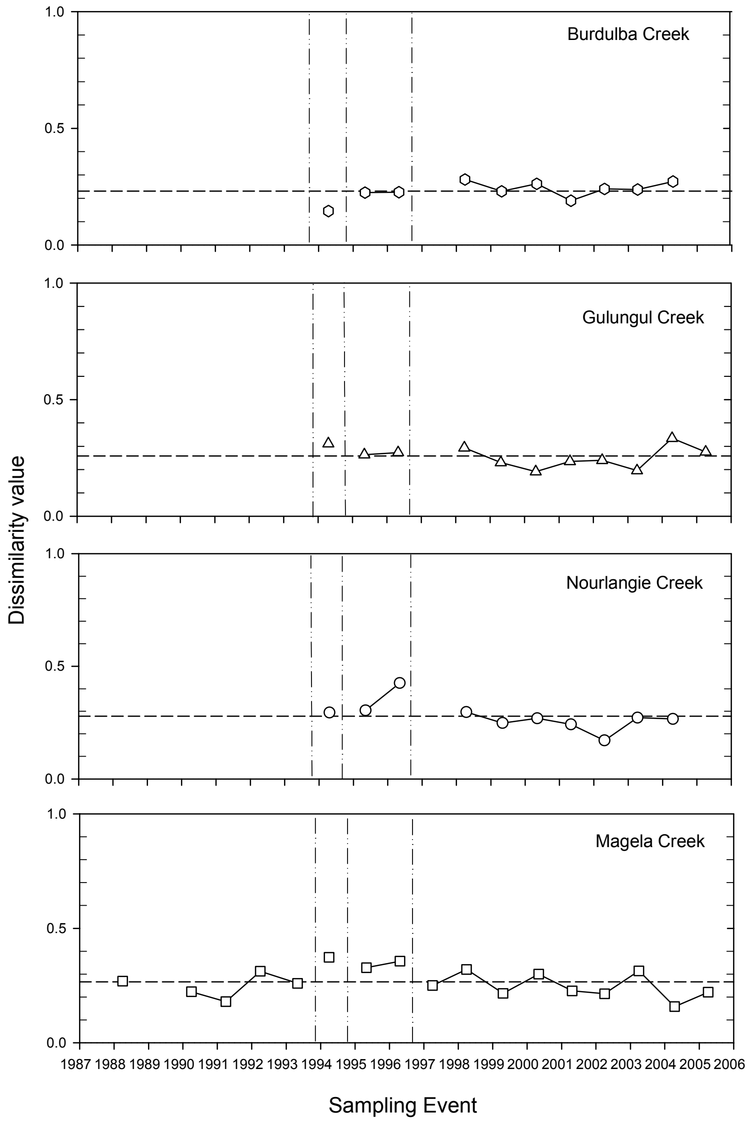
Inferences that may be drawn from the data shown in figure 1 are weakened because there are no pre-mining (pre-1980) data upon which to assess whether or not significant changes have occurred as a consequence of mining. Notwithstanding, the plots show that the mean

[1] Formerly SSD; now Ecowise Environmental P/L, Melbourne

dissimilarity value for each stream across all years is approximately the same (~0.3) and that the values are reasonably constant over time. Confirming this, single-factor ANOVA shows no significant difference in the mean dissimilarities between the two treatment groups, 'control' versus 'potentially disturbed' streams.

Figure 1 Paired upstream-downstream dissimilarity values (using the Bray-Curtis measure) calculated for community structure of macroinvertebrate families in several streams in the vicinity of the Ranger uranium mine for the period 1988 to 2005. The dashed vertical lines delineate periods for which a different sampling and/or sample processing method was used. Dashed horizontal lines indicate mean dissimilarity across years.

Processing of samples collected from the two control streams in 2005, Burdulba and Nourlangie, had not been completed by the time this report was prepared.



Dissimilarity indices such as those used in figure 1 may also be 'mapped' using multivariate ordination techniques to depict the relationship of the community sampled at any one site and sampling occasion with all other possible samples. Samples close to one another in the ordination indicate a similar community structure. Figure 2 depicts the ordination derived using the macroinvertebrate data gathered from, the sites sampled in Magela and Gulungul creeks downstream of Ranger for each year of study, together with all other control sites sampled over the same time period. Because the data-points associated with these two sites are interspersed amongst the points representing the control sites (including data from 2004 and 2005), this indicates that these 'exposed' sites have macroinvertebrate communities that are not dissimilar to those occurring at control sites.

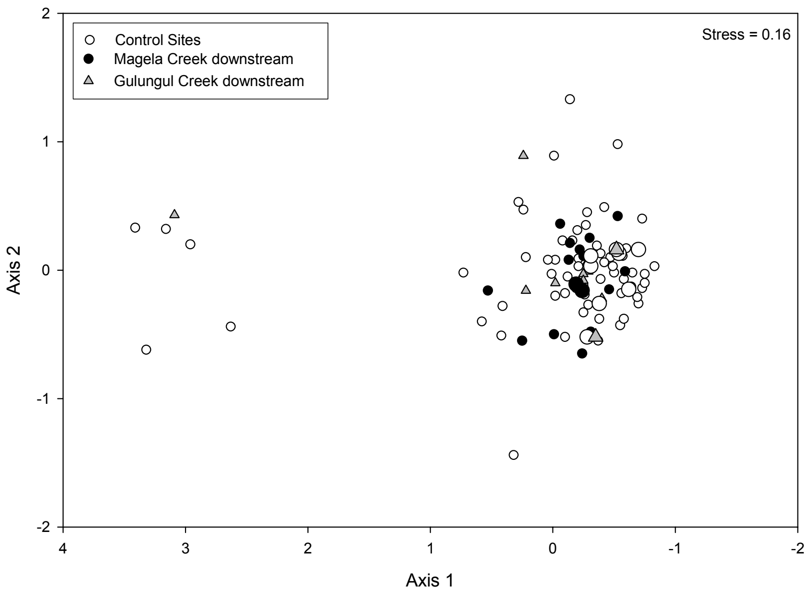


Figure 2 Ordination plot of macroinvertebrate communities sampled from sites in several streams in the vicinity of the Ranger mine for the period 1988 to 2005. Data from 2004 and 2005 are indicated by the enlarged symbols.

Collectively, these results provide good evidence that changes to water quality downstream of Ranger as a consequence of mining in the period 1994 to 2005, at least, are not sufficient to have adversely affected macroinvertebrate communities.

Reference

Faith DP, Dostine PL & Humphrey CL 1995. Detection of mining impacts on aquatic macroinvertebrate communities: Results of a disturbance experiment and the design of a multivariate BACIP monitoring programme at Coronation Hill, Northern Territory. *Australian Journal of Ecology* 20, 167–180.

Monitoring using fish community structure

R Pidgeon & C Humphrey

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

1. Visual observation data from two deep channel billabongs: Mudginberri Billabong on Magela Creek about 12 km downstream of Ranger, and directly exposed to any released mine waters (‘exposure’ billabong, 1989–present); and Sandy Billabong on Nourlangie Creek (control billabong, independent catchment, 1994–present).
2. Data from ‘pop-nets’ set in shallow weedy lowland billabongs, in various combinations, from 1994 to the present:
   - ‘Directly exposed’ billabongs in Magela Creek adjacent to and downstream of Ranger mine. These sites are directly exposed to contaminated surface flows from the minesite;
   - ‘Indirectly exposed’ billabongs in Magela Creek downstream of the mine. Whilst not directly receiving mine waste waters, the sites can receive contaminated creek water, indirectly, by back flow (‘pseudo’ controls);
   - ‘Control’ billabongs in Wirnmuyirr Creek (Winmurra) (a floodplain tributary of Magela Creek), Nourlangie Creek (Sandy and Buba) and East Alligator River (Cathedral) (true controls). These sites cannot receive contaminated water as they are in different catchments with no mining activity. (In previous annual reporting *viz* the ‘Supervising Scientist annual reports’ (2003–04 and earlier), Winmurra Billabong has been regarded as an ‘indirectly exposed’ site.)

The design for both approaches is amenable to the comparisons: (i) directly exposed billabong(s) versus control billabong(s) from independent catchments (Nourlangie Creek, East Alligator River, Wirnmuyirr Creek); and/or (ii) directly exposed billabongs versus indirectly exposed billabongs in Magela Creek, recognising that this second approach is confounded by possible movement of fish between the two lowland billabong types in the same stream system.

Since mining activities commenced at Ranger in 1979, changes unrelated to mining have occurred in stream catchments that, if not well understood, have the potential to confound conclusions drawn about the environmental impact of mining. These changes may be associated with natural climatic events or phases, or may be due directly or indirectly to invasive species removed from, introduced to, or which have increased their range throughout, the region. Hence an important ongoing task is to gain a sound understanding of the dynamics and factors affecting populations and communities of the key biota in streams adjacent to ARR minesites. In this way, changes in metrics used to summarise responses of these monitoring organisms can be correctly attributed to mining or non-mining-related causes. Alongside monitoring results for the respective studies, two such investigative studies are reported in ensuing papers of this report, focusing in fish communities sampled in deeper channel (Humphrey et al 2006) and shallow lowland billabongs (Pidgeon et al 2006).

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Fish communities in channel billabongs

C Humphrey, D Buckle & R Pidgeon

Introduction

In this sampling technique, visual observations are made upon fish communities inhabiting the littoral zones of deep, sandy-bottomed channel billabongs. Five sites are sampled in each of Mudginberri and Sandy billabongs, each site surveyed repeatedly (five times) along a 50 m transect set parallel to the shore. Typically, the transect is set immediately adjacent to steep banks with dense, over-hanging or submerged pandanus palms. Observations are made through the front of a boat with custom-made, clear, perspex-viewing dome.

The basic design entails the simple pairwise comparison of fish community data between Mudginberri (directly exposed) and Sandy (control) billabongs using multivariate dissimilarity indices. These indices and rationale for their use are explained in an accompanying monitoring paper contained in this SSR (Humphrey et al 2006). While data for Mudginberri Billabong have been gathered since 1989, only the results since 1994 are shown here, the period from which the additional control billabong (Sandy) has been sampled. A plot of the paired-site dissimilarity values using log-transformed data, from 1994 to the present, is shown in figure 1.

Dissimilarity indices may also be mapped in an ordination to depict the relationship of the community sampled at any one site and sampling occasion with all other possible samples. Shifts in fish community structure have been observed in both billabongs over time (figure 2) and while the sites do not faithfully 'track' one another from year to year, the patterns and extent of 'meandering' are not too dissimilar. In the last three years, there has been a return in both sites to a reasonably common community structure that is also similar to that found at the commencement of the paired-site study in 1994.

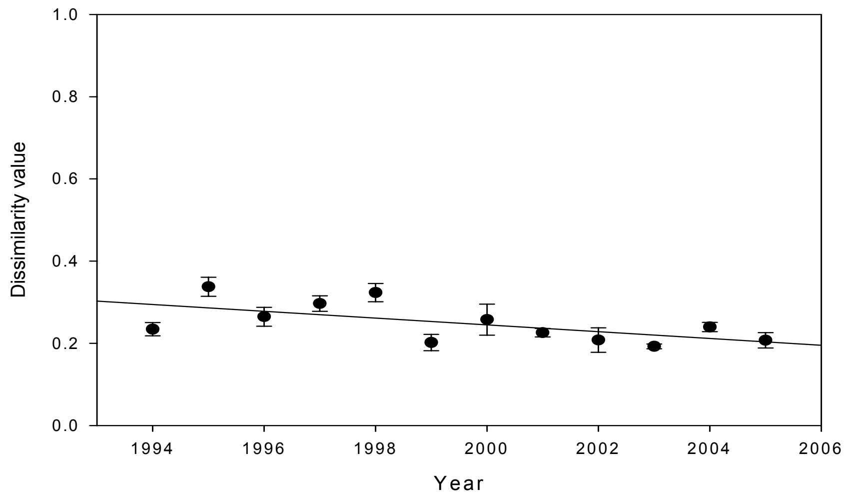

Figure 1 Paired control-exposed dissimilarity values (using the Bray-Curtis measure) calculated for community structure of fish in Mudginberri ('exposed') and Sandy ('control') billabongs in the vicinity of the Ranger uranium mine over time. Values are means (± standard error) of the 5 possible (randomly-selected) pairwise comparisons of transect data between the two billabongs, while line about the means illustrates the fitted regression (R^2 = 0.2, P = 0.0003).

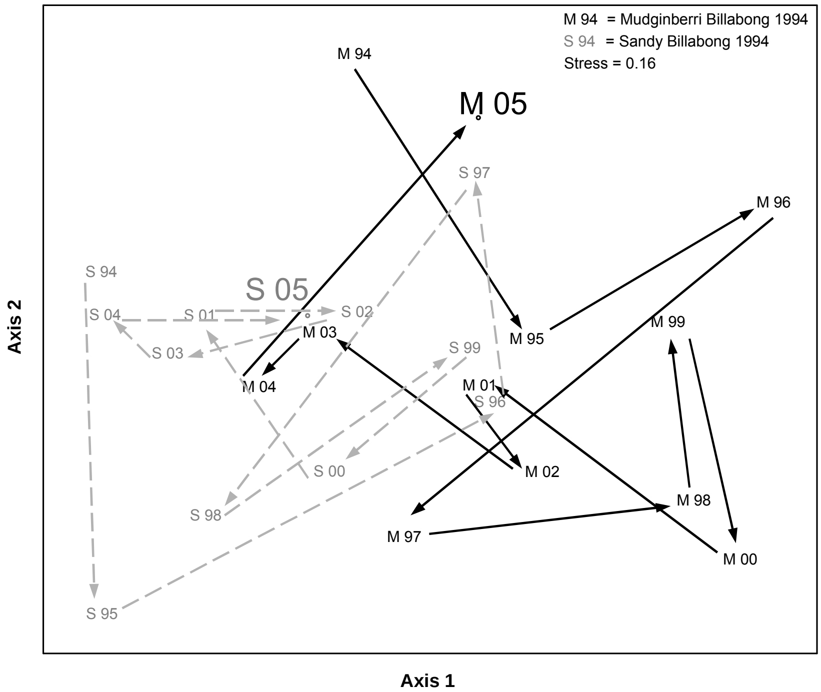

Figure 2 Ordination plot of fish communities sampled from two channel billabongs in the vicinity of the Ranger uranium mine for the period 1994 to 2005. Lines follow the trajectory of sites over time.

In the Supervising Scientist annual report for 2003–2004, a significant decline was noted in the paired-site dissimilarity measures over time (figure 1). Large discrepancies in the abundances of numerically-dominant fish species between billabongs are particularly influential in inflating dissimilarity measures. In the 2003–2004 annual report, the decline in the dissimilarity measure was attributed to the particularly high abundances of chequered rainbowfish (*Melanotaenia splendida inornata*) and to a lesser extent glassfish (*Ambassis* spp) in Mudginberri Billabong in the early years of the study, relative to Sandy Billabong. This result has subsequently been confirmed. Thus, in table 1, the influence of these numerically-dominant fish species in channel billabongs upon correlation and regression results for the dissimilarity versus time relationship is shown. Removal of each species, particularly chequered rainbowfish, reduces the significance of the decline in the dissimilarity measure. Removal of both fish species results in a non-significant result ($P>0.05$).

Table 1 Influence of numerically-dominant fish species in channel billabongs upon correlation and regression results for the paired-site dissimilarity value, and time

	Correlation (ρ)	Regression parameters	
		R^2	P
All taxa	-0.45	0.20	0.0003
Glassfish species removed	-0.36	0.13	0.005
Chequered rainbowfish removed	-0.31	0.07	0.02
Both taxa removed	-0.17	0.03	0.20

The relative abundances of chequered rainbowfishes and glassfish in both Mudginberri and Sandy billabongs are plotted as a time series in figure 3. (Sampling in Mudginberri commenced in 1989 while sampling in Sandy did not commence until 1994.) In 1996, the visual-observation sampling method was conducted relatively early in the wet-dry recessional flow period in Mudginberri Billabong, and the high counts of both fish species observed in this year reflect fish migrating upstream through the billabong. (Normally sampling commences later in the season, after significant fish migration has ceased.)

A feature of the abundance plots of figure 3 is the decline in rainbowfish in Mudginberri Billabong since 1989. Omitting anomalous 1996 data (see above), this decline is shown to be significant in regression analysis (R^2 = 0.547, p = 0.001). The decline in this fish species in Mudginberri, relative to Sandy, is the main reason for the corresponding decline in the paired-site dissimilarity measure (table 1). For this reason, possible causes of this decline were examined. Potential correlates of rainbowfish abundance were sought from water quality (natural and related to wet season wastewater discharges from Ranger mine) and quantity (stream discharge) variables.

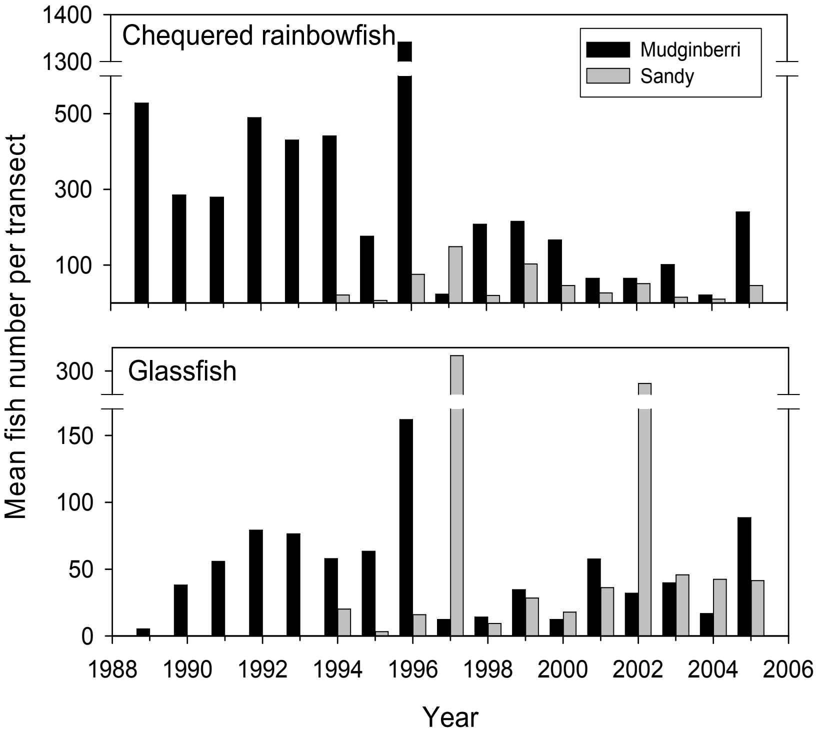

Figure 3 Relative abundances of chequered rainbowfish and glassfish in channel billabongs over time

In addition, rainbowfishes (and glassfishes) observe very significant migrations in Magela Creek after wet season spawning and recruitment on the (downstream) floodplain (ARRRI Annual Research Summary 1987–88). Thus, the abundances of these fishes in Mudginberri at the time of annual sampling reflect, to a large extent, breeding and recruitment success on Magela floodplain. (This migration phenomenon appears to be less pronounced in Nourlangie Creek (***eriss*** unpublished data), possibly explaining to some extent the smaller magnitude and/or variability in numbers of the same two fish species in Sandy Billabong.) Therefore, correlates that could explain changes to floodplain conditions over time, as these affect rainbowfish breeding and recruitment success, were also sought.

Key environmental correlates of rainbowfish abundance and decline in Mudginberri Billabong over time are shown in figure 4. These results may be summarised as follows.

Water quality associated with Ranger mine wastewater discharges

The dominant contaminants associated with Ranger mine wastewater discharges to Magela Creek are uranium, magnesium and sulphate. Uranium (U) data derived from Magela Creek prior to 2000 are unreliable, due to contamination and instrumentation problems (ie poor detection limits). Therefore, magnesium (Mg) data were analysed as a reasonably reliable, surrogate measure of mine wastewater contaminant concentrations in Magela Creek. Because Mg concentrations are naturally and inversely correlated with stream discharge in Magela Creek, the net input of Mg from Ranger was derived, this being the difference in median wet season concentration between downstream (compliance site) and upstream (control) locations. The plot of net wet season Mg concentration and corresponding rainbowfish abundance in Mudginberri Billabong for that wet season is provided in figure 4C. No significant relationship is observed. This is not surprising: concentrations of U and Mg in Magela Creek arising from mine wastewater discharges are at least two orders of magnitude lower than those known to adversely affect larval fishes, including in the case of U, chequered rainbowfish (eg Supervising Scientist annual report 2003–04, section 3.4.1 and Supervising Scientist annual report 2004–05, chapter 3, ecotoxicity research highlight).

Stream discharge and natural water quality

Since the commencement of this study in 1989, there has been a general increase in wet season rainfall and associated stream discharge in Magela Creek. Consequently, total wet season discharge in the creek is significantly and negatively correlated with rainbowfish numbers in Mudginberri Billabong (figure 4A). How higher discharge *per se* would result in lower fish numbers is not clear. However, greater discharge volumes result in greater dilution of wet season surface waters and their solute concentrations. Median wet season values of electrical conductivity (EC) of Magela Creek waters upstream of Ranger were used as a surrogate measure of solute concentrations. Not surprisingly, median wet season EC in Magela Creek is significantly and positively correlated with rainbowfish numbers (figure 4B).

Magela Creek surface waters are extremely soft and poorly-buffered, factors accentuated at high wet season flows in the creek. It is possible that early life stages of rainbowfishes are stressed under these conditions (which include relatively high acidity) and lack essential minerals for growth and development. There is some experimental evidence to support this. The fry of both chequered rainbowfish (ARRRI Annual Research Summary 1987–88) and the congener, the black-lined rainbowfish used in the SSD's creekside testing program (section 2.2.3 of the Supervising Scientist annual report for 2004–05), exhibit reduced survival when exposed to creek waters during high flow events.

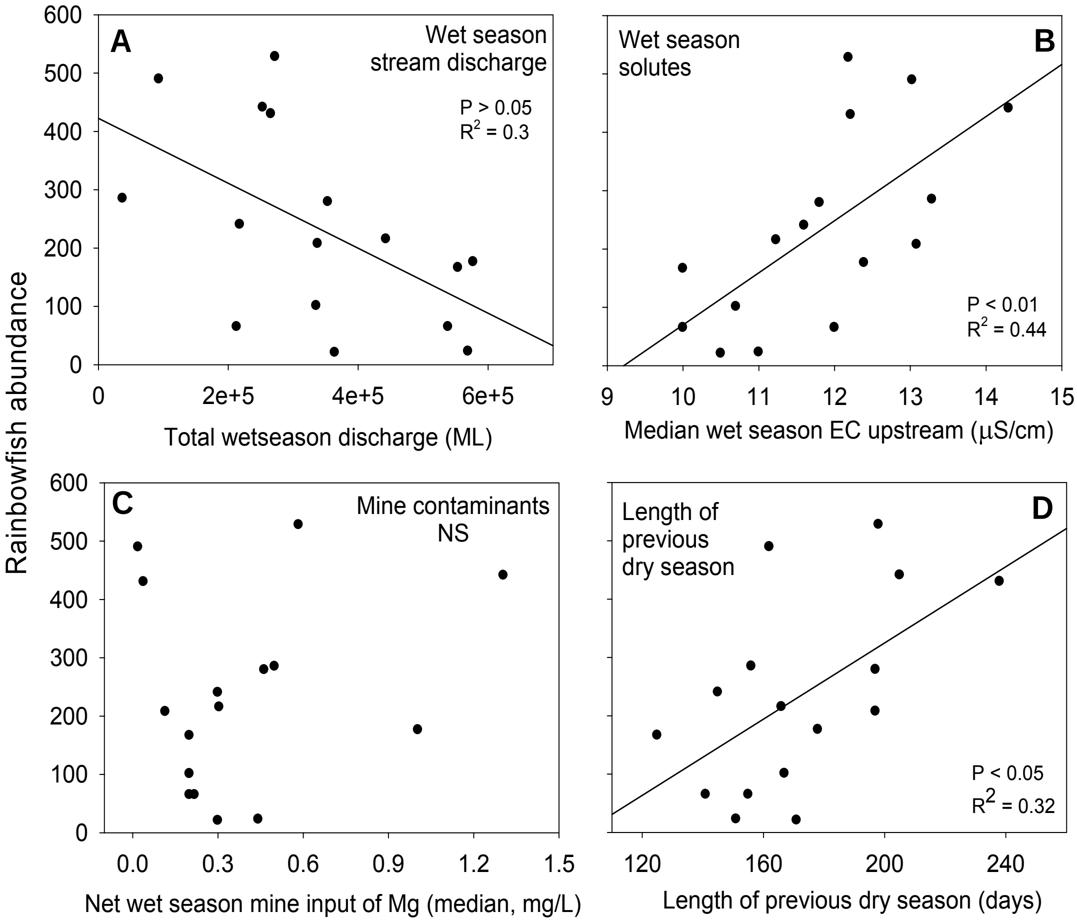

Figure 4 Environmental correlates of rainbowfish abundance in Mudginberri Billabong, 1989–2005

Conditions on Magela floodplain

Changes to vegetation communities on Magela floodplain, the main breeding area and recruitment source for chequered rainbowfish in Magela Creek, may have adversely affected rainbowfish populations. In particular, a number of grass species are rapidly expanding in range and densities on the floodplain, due partly to removal of feral buffalo that once grazed on these grasses and acted as a form of control. A particularly aggressive species is the exotic para grass (*Urochloa mutica*) which is currently expanding its area of coverage at 14% p.a. Without management it could dominate the floodplain in 15 to 20 years. With the presence of satellite patches of para grass, this could be a conservative time frame (Bayliss et al 2006). The recent rapid expansion of para grass on Magela floodplain corresponds to the period of decline of chequered rainbowfish in Mudginberri Billabong. It is quite possible that the expansion of this and other exotic and native grasses (especially native *Hymenachne*) has had some adverse effects on recruitment of rainbowfish.

Impacts of both para grass and native *Hymenachne* on floodplain biota were studied by Douglas et al (2002). Stands of both these grasses contained fewer fish species and lower fish abundance than areas of more open vegetation dominated by wild rice (*Oryza meridionalis*). Consequently, any increase in the area covered by either para grass or hymenachne could have adverse effects on the recruitment of fish that utilise floodplain habitats in the wet season into dry season refuges in floodplain billabongs and upstream channel billabongs.

Unfortunately, there are no comparable data on possible grass expansion for the floodplain of Nourlangie Creek downstream of Sandy Billabong.

A feature of floodplain hydrology that may also affect fish breeding success and recruitment is the period of drying of the floodplain prior to annual re-wetting. The so-termed 'flood-pulse' theory predicts and shows that primary and secondary production of floodplains is dependant upon the degree of seasonal drying and inundation. In particular, chemical cycling and nutrient release are dependent upon, and enhanced by, sediment and soil drying prior to wet season inundation. For Magela Creek, a shorter previous-dry-season and reduced drying of the floodplain may reduce ensuing wet season production on the floodplain nursery zone. The relationship between length of previous dry season (ie from Magela Creek cease-to-flow to commencement of flow, downstream of Ranger) and Mudginberri rainbowfish numbers is, in fact, significant (figure 4D), lending some support to this hypothesis.

It is worth noting that the expansion of grasses on Magela floodplain will have lead to greater soil water retention and thereby, and independently, accentuated any reduction in floodplain drying observed since this monitoring study commenced.

Summary

The decline in rainbowfish numbers in Mudginberri Billabong over the period 1989 to 2005 does not appear to be related to any change in water quality associated with mine wastewater discharges from Ranger. Over time with further monitoring and analysis, it may be possible to distinguish and identify natural stream water quality, discharge and/or floodplain habitat factors responsible for changes to fish populations in Magela Creek billabongs. These causal factors may then be modelled to account for variation in monitoring response variable(s).

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Fish communities in shallow lowland billabongs

R Pidgeon, R Luxon & D Buckle

The design of this monitoring technique is described in an accompanying introductory paper contained in this report (Pidgeon & Humphrey 2006).

Results for 2004–05

The abundance of fish captured by pop-net sampling in shallow billabongs for the period 1994 to 2005 is shown in figure 1.

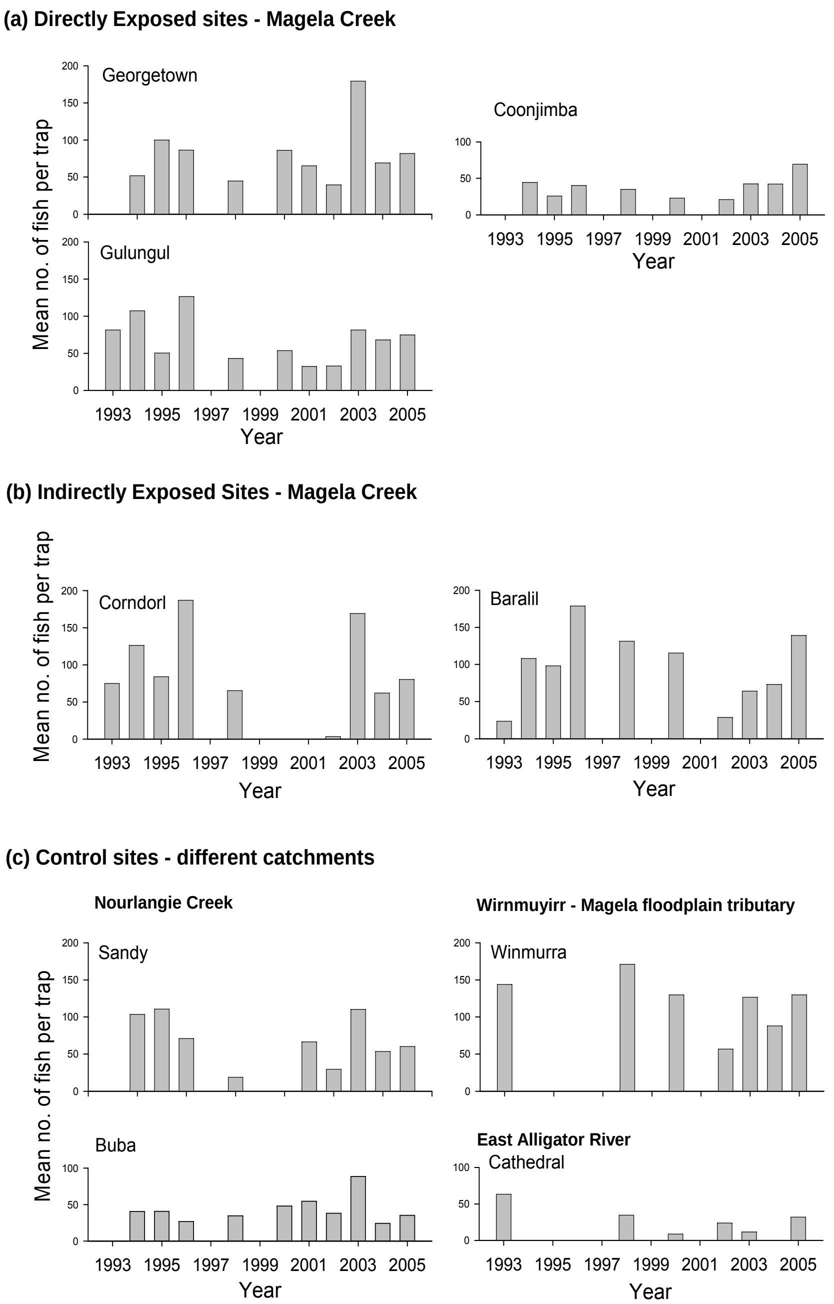

Figure 1 Relative abundance of fish in billabongs with different degrees of exposure to contaminants from Ranger uranium mine, 1994–2005. Not all sites have been sampled each year. Sampling in Djalkmara Billabong was discontinued after mining at Pit 3 closed its connection to Magela Creek.

Abundances in 2005 were similar to, or slightly greater than in 2004. The changes in fish abundances in 2005 were, with one exception, all within the range of natural variation observed for each location since sampling commenced in 1994. Fish abundance in Coonjimba Billabong was the highest so far recorded for this site.

The number of fish species recorded in each billabong has varied only slightly over the 1994 to 2005 period by comparison with fish abundance (data not shown here).

Multivariate ordination was used to compare the fish community structures in the three exposure types (figure 2). The area enclosed by data points for each billabong in years prior to 2005 is shown as a polygon to indicate their 'natural' location in the ordination space. Whilst some sites overlap considerably, the data points for different sites tend to occupy different areas of the ordination indicating differences in community structure. Formal statistical testing of the ordination patterns shows significant differences among some sites and amongst the three exposure types (ANOSIM, R= 0.37–0.42, P = 0.001).

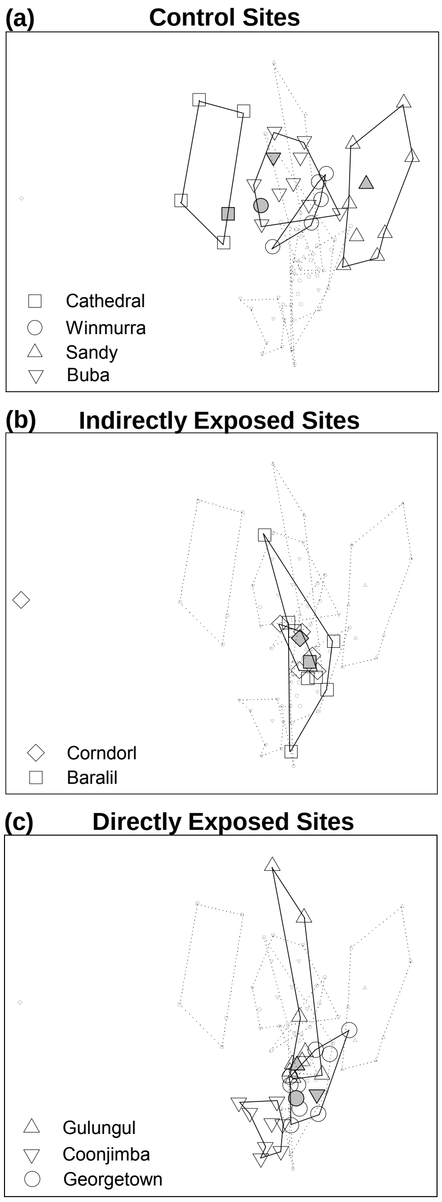

Figure 2 Ordination plots of fish communities in shallow billabongs near Ranger uranium mine with different potential exposure to contamination from mine wastes, for 1994 to 2005. Ordination calculated for 2 dimensions, stress = 0.18. The areas enclosing points for years 1993 to 2004 for each billabong are shown as polygons. (Only the relevant polygons are highlighted.) The position of data for 2005 is indicated separately as filled symbols for comparison with previous years.

Nevertheless, the most important feature of the ordination pattern is that the relative position of sites has remained quite constant over time. The reasonably-well defined locations of each of the billabongs in the ordination over the 11 years of sampling provide a useful basis for detecting and assessing change. In particular, departure from the natural patterns in community structure in exposed sites could indicate adverse effects of mining activity. The potential of this detection procedure was indicated by an outlying data point for Corndorl Billabong in 2002 that was related to an abnormal cover of the exotic floating weed, *Salvinia molesta* (Supervising Scientist annual report, 2002–2003).

The ordination results for 2005 lie within, or very close to, these natural positions in the ordination space and indicate there was no discernible effect of mining activity on fish communities. This was supported by the temporal pattern of multivariate dissimilarities between control and direct exposure sites (figure 3). There were no significant differences among years. The slight trend of increase over time is not statistically significant, nor did closer examination of the numerically-dominant fish species indicate any trends nor divergence in abundances of fish between direct exposed and control sites (cf channel billabong analysis, described above).

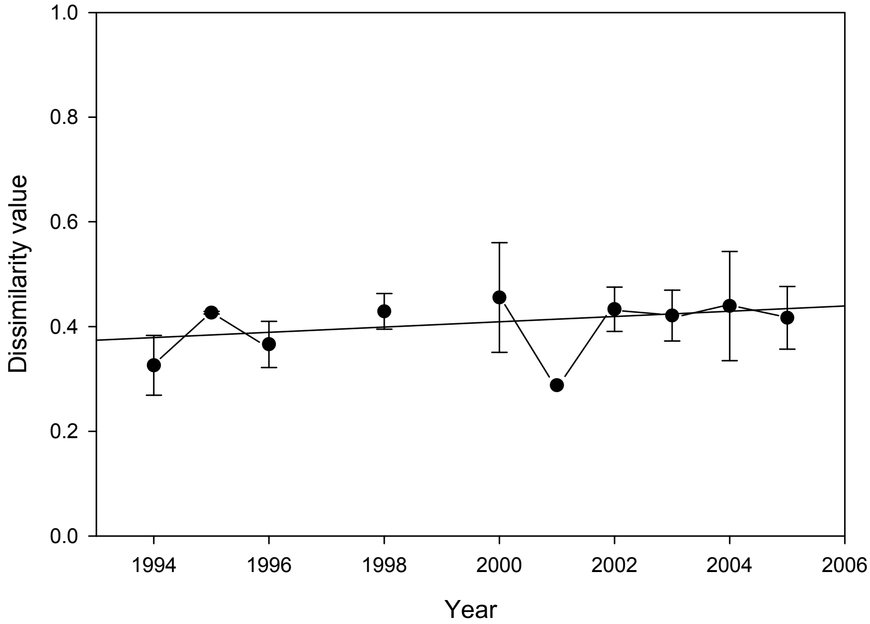

Figure 3. Paired dissimilarity values (using the Bray-Curtis measure) calculated for community structure of fish in 'directly exposed' Magela and 'control' Nourlangie and Magela billabongs in the vicinity of the Ranger uranium mine over time. Values are means (± standard error) of the (up to) 3 possible pairwise billabong comparisons: Coonjimba vs Buba, Gulungul vs Winmurra, and Georgetown vs Sandy billabongs. Line about the means illustrates the fitted, but non-significant, regression.

The small variation in dissimilarity values for fish communities in channel billabongs and the similarity of 2005 fish communities in shallow and channel billabongs to the respective communities found in previous years indicate there is no evidence of any adverse effects of mine waste waters arising from the Ranger minesite on fish communities of Magela Creek.

Potential impacts of cane toads

It is now three years since cane toads (*Bufo marinus*) invaded the area of billabong sampling sites on Nourlangie Creek and two years since they appeared at Magela Creek billabong sites. Possible effects of cane toads on fish communities are examined in figure 4 by comparing numbers of fish in the two catchments before and after cane toad arrival. The fish were grouped into three trophic guilds with different potential risk from the presence of toxic toad life stages: 'carnivores' (spangled grunter, mouth almighty, sleepy cod); 'benthic omnivores' (four species of eel-tailed catfish); and 'microphagic omnivores' (glassfish, rainbowfish, hardyheads). There is no evidence of a decline in any of the trophic groups following toad arrival. Consequently, it is concluded that there has been no measurable impact from cane toads on billabong fish communities. This result contributes valuable information to national assessments of risk to biodiversity posed by this invasive species. It also indicates that this invasive species is unlikely to confound assessments of mining impact at Ranger and supports the continued use of this monitoring technique for this role.

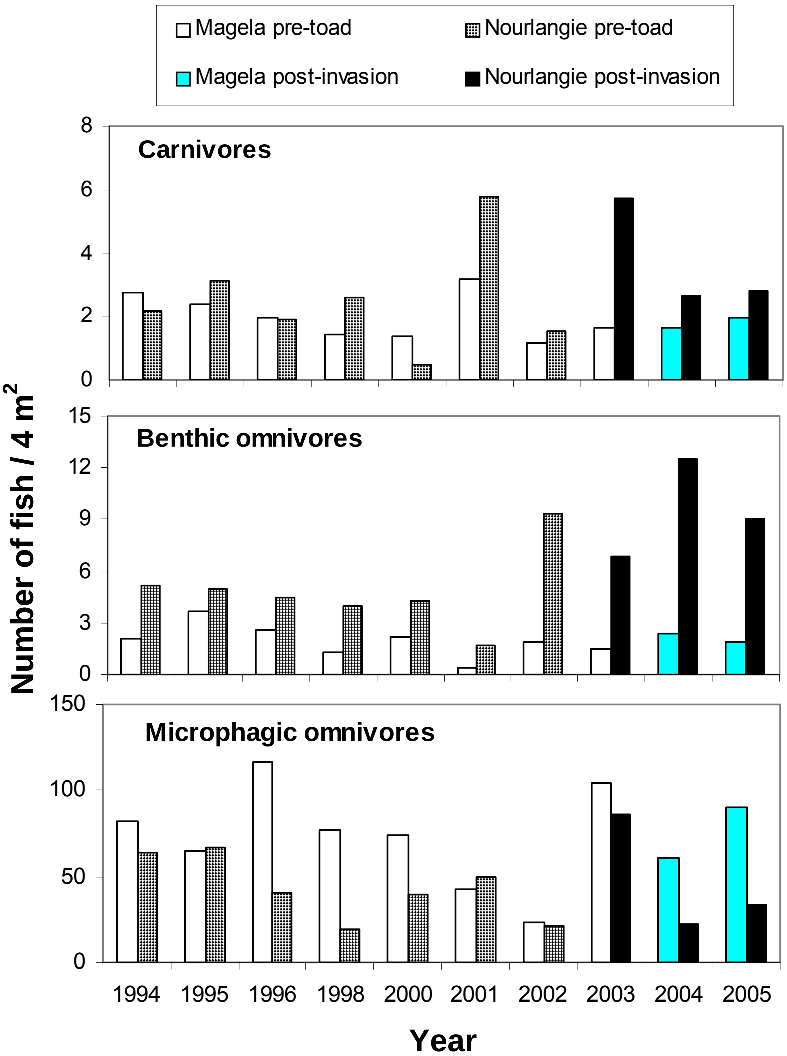

Figure 4 Temporal patterns of abundance of fish in shallow billabongs before and after the arrival of cane toads in two catchments, Nourlangie Creek and Magela Creek

Reference

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Publication of protocols for SSD's stream monitoring program in Magela Creek and Quality Control and Quality Assurance of SSD's stream monitoring program

C Humphrey

Background

Protocols for SSD's stream monitoring program are being prepared for publication. Progress in preparing these protocols was reported to ARRTC in late February 2005. Key summary issues provided to ARRTC included:

1. Six of eight protocols for environmental monitoring of streams associated with the Ranger mine site have been prepared for publication in the SSR series. A corresponding operational manual – working documents with full and more complete details of methods and procedures – is being prepared for each of the protocols.
2. Two protocols associated with bioaccumulation (in freshwater mussels and fishes) continue to be drafted following a review of the bioaccumulation program (see Sauerland et al 2006).
3. Data analysis aspects of the protocols are also currently under revision with improvements to data analysis approaches to be incorporated into the protocols prior to publication of the SSR.
4. Considering items 2 and 3, the protocols will be published in the first half of 2006.
5. QA/QC aspects of the protocols were reported to ARRTC separately (Humphrey et al 2005).

Regarding item 5, ARRTC was provided with the general principles applied to documenting QA/QC steps in SSD's environmental monitoring protocols and in implementing the steps in the routine conduct of the monitoring program. A risk analysis of critical steps in each protocol is being undertaken, the outcome of which will determine the level of auditing, internal and external, as well as training to devote to steps of the protocols. By way of example, such a risk analysis, combined with precedent and best-practice elsewhere, was undertaken for two of SSD's monitoring protocols and presented to ARRTC. The committee agreed that (i) QA/QC for SSD's monitoring program be developed according to this logic, (ii) the balance of internal and external QA/QC and training identified in the exemplary risk analyses was appropriate, and (iii) following publication of the protocols, QA/QC findings would be reported annually in an SSR of monitoring results and, as such, are embedded in the protocols, both in implementation and as an annual reporting outcome.

Progress to date

Statistical advice from CDU (Dr Keith McGuinness) has been sought for sections of the protocols dealing with design and analysis. This advice is being incorporated into the final drafting of protocols.

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Review of the bioaccumulation monitoring program

C Sauerland, B Ryan, C Humphrey & D Jones

Background

Detection of increases 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. Measurements in fish and mussel tissues have been made since 1970. Since 2002, bioaccumulation data have also been gathered from a control site (Sandy Billabong).

A review of the bioaccumulation study of metals and radionuclides at Ranger is currently being undertaken with the aim of developing, as far as possible, a common metals and radionuclide sampling and analysis program, to avoid any unnecessary duplication between programs. As part of the review, all available bioaccumulation data for Ranger (mussels and fish, both billabongs) are being compiled and reported. The review includes an assessment of the data quality, and an assessment of whether any changes in metal/radionuclide concentrations are mining-related and culminates with the production of suitable protocols for continued monitoring.

Progress to date

The bioaccumulation of radionuclides and metals in freshwater mussels from Mudginberri and Sandy billabongs between 2000–2003 was reported by Ryan et al (2005a). A second report on the bioaccumulation of radionuclides and metals in freshwater mussels of the upper South Alligator River (Ryan et al 2005b) provides a dataset for comparison from another region in the Alligator Rivers Region.

All available bioaccumulation data for metals in fish and mussels collected between 1970–2003 from Mudginberri and Sandy billabongs by different organisations have been compiled and summarised in an inventory. These results will be reported shortly. As an example, figure 1 illustrates that uranium concentrations measured in the flesh of the forktail catfish (*Arius leptaspis*) and the freshwater mussel *Velesunio angasi* are generally consistent across different organisations, are generally low and similar for both billabongs, and have not significantly increased since mining started 1980 until 2003. The quality of SSD fish data currently being assessed against an extensive set of quality control samples taken in 2003 (replicate, blank and spiked samples; interlaboratory comparison).

Preliminary results from an additional and related review, which was conducted as part of the trophic transfer study (various biota), were reported by van Dam et al (2005) (see summary for ARRTC KKN 1.2.1). The current review and the aquatic pathway section of the trophic transfer study will be merged.

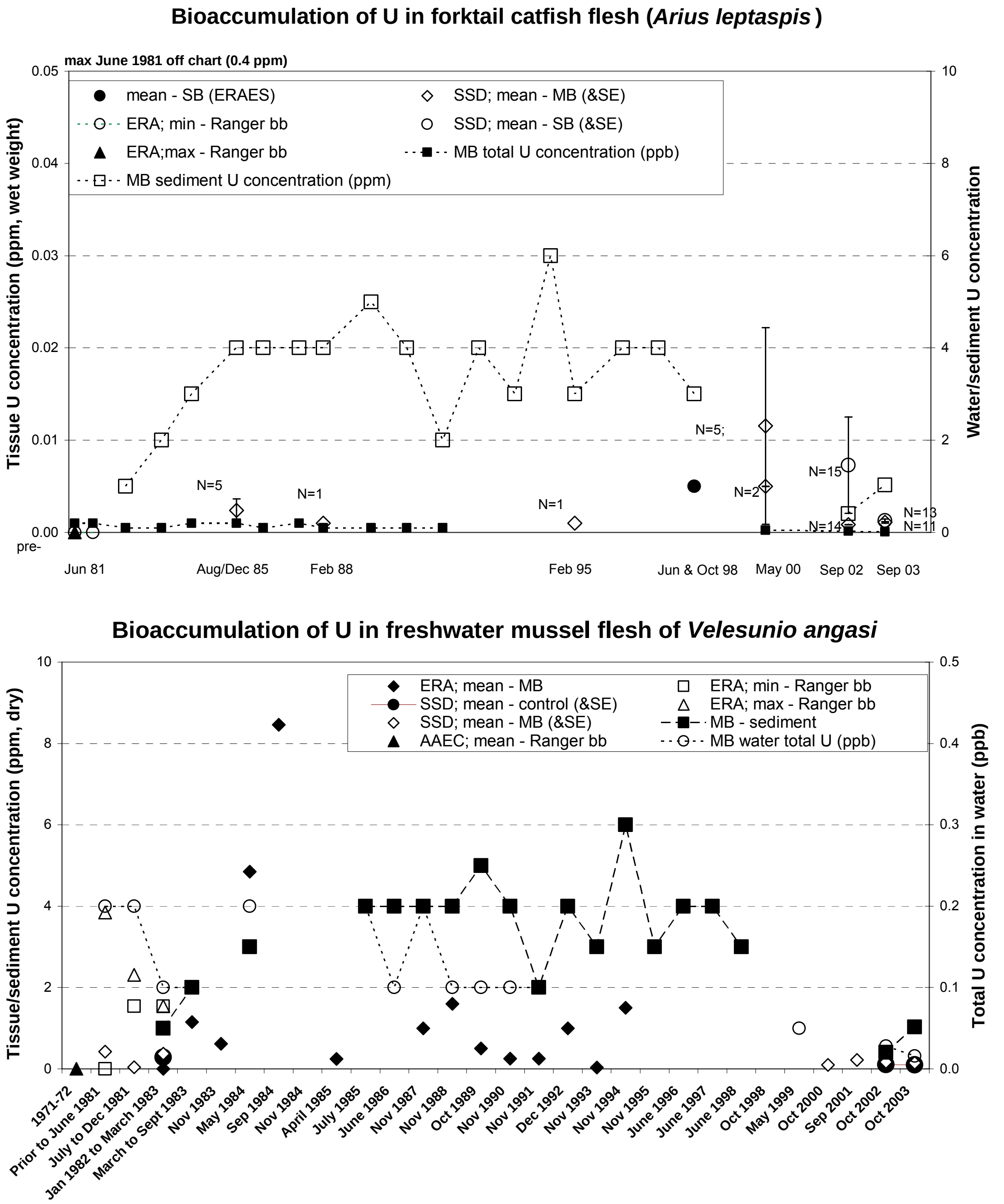

Figure 1 Mean or minimum and maximum values of uranium concentrations in flesh of the forktail catfish and the freshwater mussel *Velesunio angasi* collected in Sandy Billabong (SB), Mudginberri Billabong (MB) or other billabongs on the Ranger lease (Ranger bb) between 1980–2003 by the Supervising Scientist Division (SSD), Energy Resources of Australia (ERA) and in 1971–1972 by the Australian Nuclear Science and Technology Organisation (previously AAEC), and uranium concentrations in water and sediment. SE = standard error and N = number of samples.

A small workshop was conducted in September 2005 to report on progress made towards meeting the objectives of the bioaccumulation review. The outcomes of the workshop are currently being compiled for reporting. Summary items arising from the review included:

- Metal and radionuclide body burdens in mussels and fishes from Mudginberri Billabong are generally low, with no evidence of trends through time.
- Average metal concentrations of fish and mussel flesh samples are well below the maximum allowable levels for human consumption (Commonwealth of Australia 2005).

Copper and zinc average concentrations in fish tissues are above the generally expected levels (Commonwealth of Australia 2001) at both the 'impact' and control site reflecting the naturally higher metal and radionuclide levels in the Alligator Rivers Region

- Concentrations of metals and radionuclides in mussels from Mudginberri Billabong appear to be related to age, growth rates and location (viz sediment quality). The need to better characterise sediment quality was recognised for future sampling.
- Metal concentrations in fish are not related to fish size or weight but may vary by orders of magnitude dependent on the type of organ. Calcium, magnesium, manganese, strontium, barium, lead and uranium are preferentially incorporated into bones while antimony, selenium, mercury, tin and zinc are highest in liver samples.
- Concentrations of radionuclides and a number of metals in mussels from Mudginberri Billabong are generally higher than mussels from Sandy Billabong. Naturally higher catchment concentrations of constituent elements in Magela Creek compared with Nourlangie Creek catchment are likely to be the cause, together with lower concentrations of calcium in Mudginberri Billabong waters compared with Sandy (likely to contribute higher radium concentrations at least, in Mudginberri mussels).
- A stream-lined bioaccumulation sampling program was devised for freshwater mussels and fish covering radionuclides and metals. Targeted species are *Arius leptaspis* and *Velesunio angasi* as they are the high-level bioaccumulators and their monitoring data set is the most extensive.
- The higher concentrations of radionuclides and a number of metals in mussels from Mudginberri Billabong compared with mussels from Sandy Billabong warrants additional sampling of mussels in Magela Creek upstream of Ranger to determine the extent to which the Ranger mine contributes to the total concentrations of elements in Mudginberri mussels.

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Surface water radiological monitoring in the vicinity of Ranger and Jabiluka

C Sauerland, P Medley & J Sellwood

Introduction

Surface water samples in the vicinity of the Ranger and Jabiluka project areas are regularly monitored for radium-226 (^{226}Ra) to assess a change, if any, in the ^{226}Ra activity concentration downstream of the mine sites and the potential risk of increased exposure to radiation via the biophysical pathway due to mining activities.

A limit of 10 mBq/L as increase above natural background in total ^{226}Ra concentration in surface waters downstream of Ranger has been defined for human radiological protection purposes (Klessa 2001) and is based on the potential dose received from the ingestion of ^{226}Ra in the freshwater mussel *Velesunio angasi* (Martin et al 1998). This limit of 10 mBq/L is applied to the wet season median difference (Sauerland et al 2005) (figure 1). It is calculated by taking the median values at both the downstream and upstream sites for each wet season, and then substracting the upstream median from the median at the downstream site.

Methods

Water samples are collected weekly in Magela creek and monthly in Ngarradj on both upstream and downstream sites of the project areas according to the surface water monitoring protocol (Sauerland & Iles 2005). All Ngarradj samples and Magela creek samples from alternate weeks are analysed for total ^{226}Ra (ie combined filtered and particulate fraction) following a method described in Medley et al (2005). The remaining fortnightly samples for Magela Creek are combined into two wet season composite samples, one for the upstream site and one for the downstream site samples.

Results

Magela Creek

^{226}Ra results for the 2004–2005 wet season are compared in Figure 1 to wet season data from 2001–2004. The data shows very low levels of ^{226}Ra in Magela Creek. A paired two-tailed t-test (95% confidence interval, N = 45, T-Value = 1.04, P-Value = 0.304, Power = 0.15) indicates that the ^{226}Ra concentrations are not significantly different at the Magela creek downstream and upstream sites between 2001 and 2005. Moreover, Figure 1 shows that total ^{226}Ra activity concentrations at the upstream site can be higher than at the downstream site. The ^{226}Ra concentration of 8.8 mBq/L in a sample collected on the 15th of February 2005 at the upstream site is most likely due to a larger contribution of fine sediments than are present naturally in the Magela creek catchment (Murray et al 1993).

Figure 2 illustrates the distribution of total ^{226}Ra activity concentrations in Magela Creek and Ngarradj. Values are mostly situated between 1 and 5 mBq/L but outliers can be as high as

11 mBq/L. The analysis of chemical blanks, duplicates and spiked blanks (not shown here) indicates that outliers were unlikely to be due to contamination during the high-resolution alphaspectrometric procedures. For example, the results of duplicate analysis were always within the range of their intrinsic counting error that is due to counting statistics (indicated by error bars in figure 1 and figure 3).

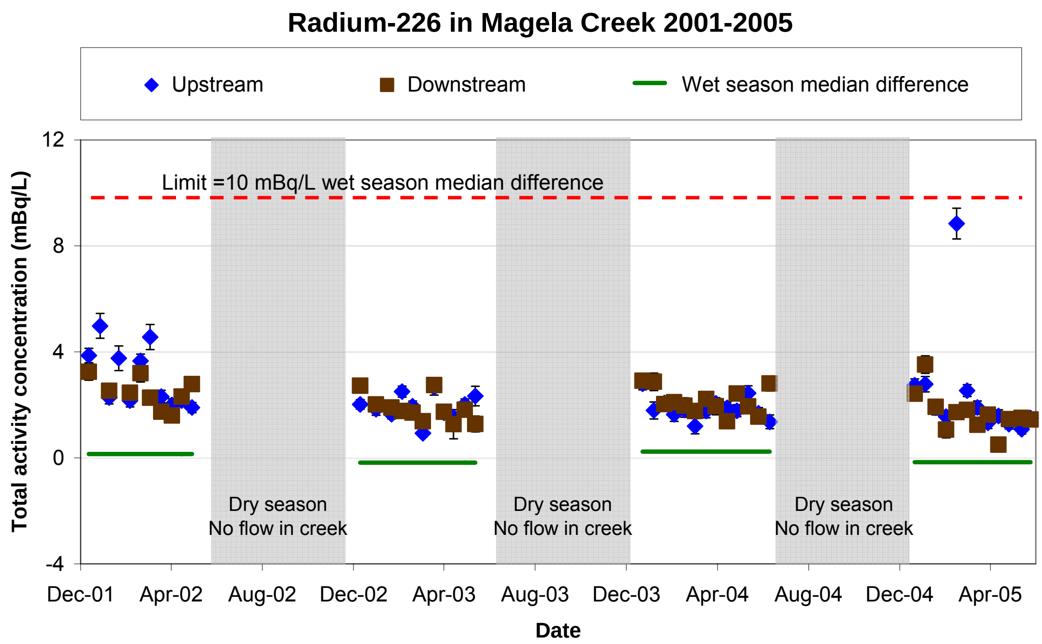

Figure 1 Time series of total radium-226 activity concentrations in Magela Creek (2001 to 2005); error shown is based on counting statistics only

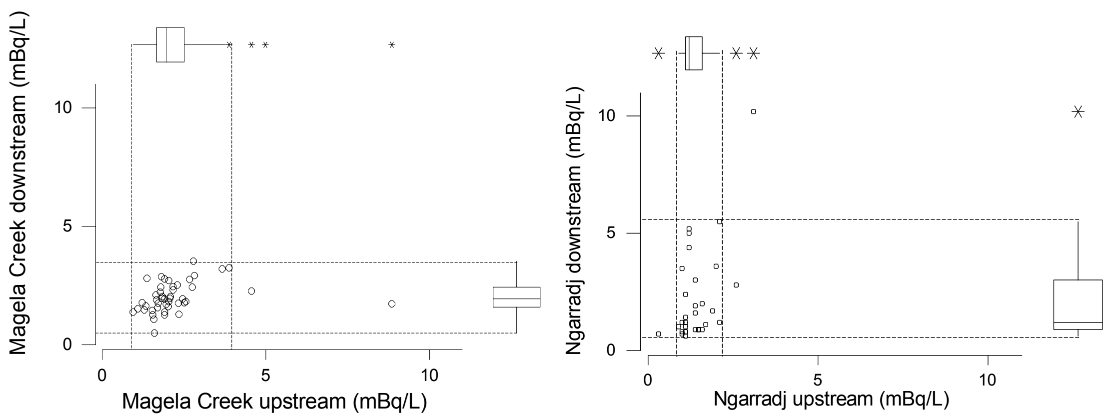

Figure 2 Scatter plot for total ^{226}Ra activity concentrations in Magela Creek and Ngarradj with boxplots in each direction in the margins of the x- and y-axes (rectangular boxes represent roughly the middle 50% of the data; asterisks represent outliers; dashed lines indicate the general extent of data.

Table 1 shows the median and standard errors for individual wet seasons and for the entire study period. The '*wet season composite samples*' (not shown) for both the upstream and downstream locations compare well to the wet season median but have a lower variability due to the compositing (eg in 2004–05 the '*wet season composite sample*' from Magela Creek was 2.3 ± 0.1 mBq/L for duplicates from both the upstream and downstream site).

Table 1 Statistics for total ^{226}Ra activity concentrations [mBq/L]

In Magela Creek		All years	2001–02	2002–03	2003–04	2004–05
Median and standard error	upstream	2.0 (± 0.2)	2.3 (± 0.3)	2.0 (± 0.1)	1.8 (± 0.1)	1.7 (± 0.6)
	downstream	2.0 (± 0.1)	2.5 (± 0.2)	1.8 (± 0.2)	2.0 (± 0.1)	1.6 (± 0.2)
Wet season median difference		N/A	0.2	- 0.2	0.2	- 0.1
In Ngarradj		All years	2001–02	2002–03	2003–04	2004–05
Median and standard error	upstream	1.2 (± 0.1)	1.2 (± 0.2)	1.4 (± 0.2)	1.1 (± 0.1)	1.3 (± 0.1)
	downstream	1.2 (± 0.3)	3.0 (± 0.9)	1.1 (± 0.5)	0.9 (± 0.3)	1.0 (± 0.3)
Wet season median difference		N/A	1.8	- 0.3	- 0.2	- 0.3

Based on the available data, the wet season median difference for all wet seasons from 2001 to 2005 is approximately zero (see table 1). The available data for the four sampling seasons indicate that ^{226}Ra levels in Magela Creek are due to the natural occurence of radium in the environment and that radium originating from the Ranger mine has not caused any impact on human health.

Ngarradj

^{226}Ra results in Ngarradj are available for the 2001–02, 2002–03, 2003–04 and 2004–05 wet seasons. The data shows that ^{226}Ra levels are very low in Ngarradj (see table 1). A paired two-tailed t-test (95% confidence interval, N=34, T-Value = -2.36, P-Value = 0.024, Power = 0.83) implies that ^{226}Ra concentrations are significantly different between the Ngarradj downstream and upstream sites between 2001 and 2005. An increase in ^{226}Ra activity concentrations due to the Jabiluka project can therefore not be excluded. However, it is more likely that the difference in downstream and upstream activity concentrations measured in 2001–02 were due to a late dry season fire that affected only the catchment downstream of the upstream sampling site (Evans et al 2004).

Figure 3 shows that ^{226}Ra activity concentrations at the Ngarradj downstream site were similar to those at the upstream site since December 2003, coinciding with the establishment of the long-term care and maintenance phase at Jabiluka in the 2003 dry season.

The wet season median difference (figure 3) in the three sampling seasons is very low, indicating that human health was not adversely affected by the presence of ^{226}Ra in Ngarradj from the Jabiluka project.

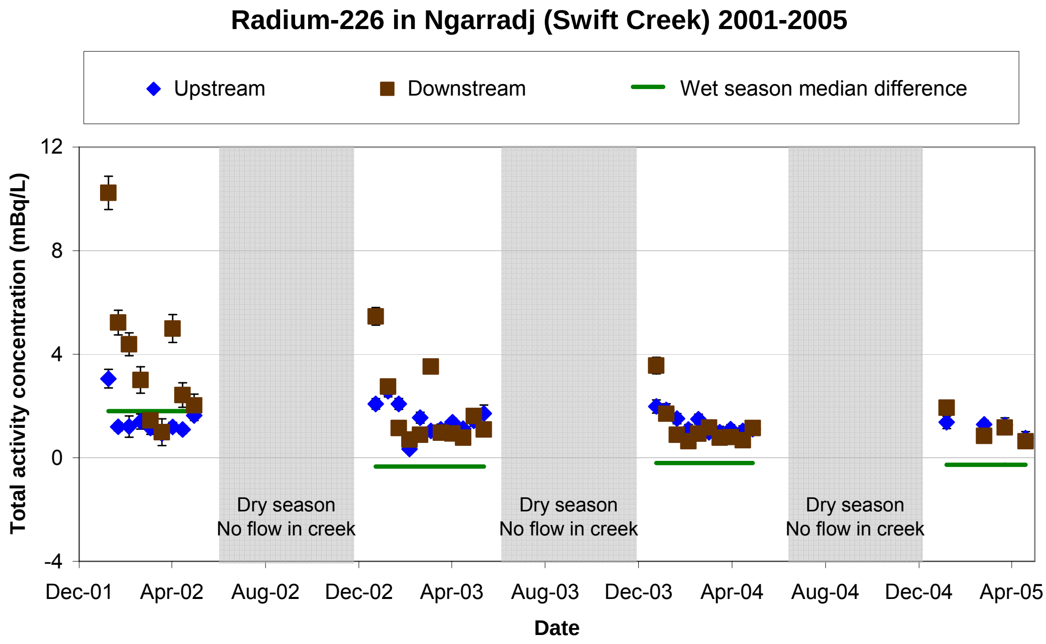

Figure 3 Time series of total radium-226 activity concentrations in Ngarradj (2001 to 2005); error shown is based on counting statistics only

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Surface water transport of uranium in the Gulungul catchment

C Sauerland, K Mellor[1], D Parry[1] & A Bollhöfer

Introduction

The aim of this project is to investigate the cause of elevated concentrations of uranium and some ions that were detected at the Gulungul Creek downstream monitoring site over the month of January 2004 and, to a lesser extent, in previous wet seasons. These concentrations, higher than those at the upstream site, coincided with higher EC values and lower pH values. The study is part of an Honours project in collaboration with Charles Darwin University, and will integrate radioanalytical, physico-chemical and hydrological transport aspects relating to contaminant transport in the Gulungul catchment.

Methods

During a field trip in the 2004 dry season, it was observed that the overland flow from the Tailings Dam South Road Culvert (TDSRC) results in a visible channel with wetland vegetation that flows into Gulungul Creek just upstream of the midstream monitoring site, GCMS. Consequently, three field trips were undertaken in the 2005 wet season (8 February, 18 March & 10 May) during which samples were taken in the Gulungul Creek catchment: upstream (GCUS), downstream (GCDS) and at several locations in the vicinity of the midstream site (GCMS), ie 'GCMS–10 m', GCMS–50 m, 'GCMS+50 m' and 'GCMS+150 m'. Samples were also taken from V-notches at TDSRC, the overland flow from TDSRC (TDSRC flow), a spring tributary flow (Spring) and from a swampy area of another suspected spring (Lower Spring).

Metal analyses of the samples, including uranium, were conducted via ICPMS at Charles Darwin University. Uranium concentration and activity ratios ($^{234}U/^{238}U$) were measured via alpha spectrometry at ***eriss*** (Martin & Hancock 2004) in order to identify uranium activity ratios of contaminating endmember(s).

Activity ratios measured downstream will be compared with ratios modelled via a mixing of various sources. Samples collected during the field trips in 2005 will be analysed as well as selected samples that were collected as part of the routine surface water quality monitoring between 2003 and 2005.

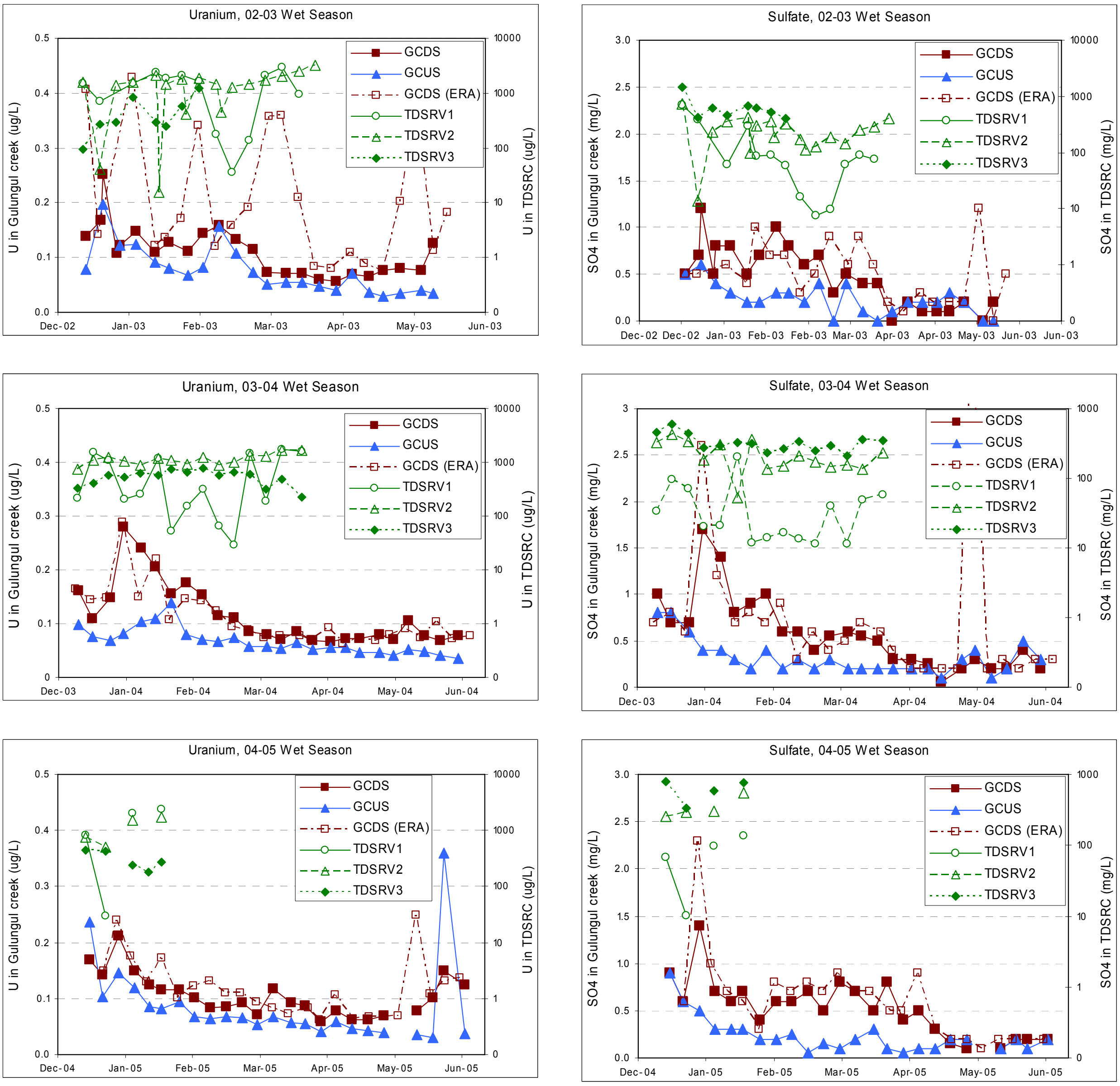
Results

Figure 1 illustrates the variations in uranium and sulfate concentrations in the samples collected from Gulungul creek and TDSRC flows over the last three wet seasons.

Review of selected concentrations for samples collected on 18 March 2005 shows little difference in concentrations among the samples collected in the vicinity of the midstream

1 Charles Darwin University, Darwin NT.

location and at GCDS, indicating that the flow from the contaminant source may enter the creek over a larger area most likely upstream of the sampling points adjacent to GCMS (table 1). Key indicators for Spring and TDSRC, also noticeably elevated at GCDS, are copper, sulfate and uranium. The difference in the indicators' concentrations between GCDS and GCUS confirm that both, Spring and TDSRC, are potential contamination sources, but the Spring's location downstream of GCMS makes it an unlikely source for the increase observed at GCDS on this field trip.



F igure 1 Time series of U and SO_4 concentrations at Gulungul Creek upstream (GCUS) and downstream (GCDS), and TDSRC V-notches between 2002 and 2005. GCDS data taken by ERA are shown as comparison.

During the field trip on 10 May 2005 however, several other dry tributaries entering the creek could be identified upstream of GCMS, which may originate from TDSRC flow, implying that previous sampling may not have extended far enough upstream. Once flow data for the TDSRC V-notches is received from ERA, a comparison of loads of the key indicators over all wet seasons since 2000 may indicate if TDSRC flow indeed contributed significantly to the observed increases between upstream and downstream sites.

Table 1 EC, pH, selected metals and major ions for samples collected 18/03/2005

Site	EC (µS/cm)	pH	As (µg/L)	Cu (µg/L)	Mg (µg/L)	Mn (µg/L)	SO_4 (mg/L)	U (µg/L)
Spring	130	6.1	0.2	0.16	12.4	11.6	53.1	5.92
TDRSC-V2	380	7.4	0.3	5.67	49.8	2490	168	1150
TDSRC-V3	693	7.5	0.25	1.32	92.1	1100	390	743
TDSRC flow at road	56	6.6	0.15	0.29	5.1	5.36	17.8	0.858
TDSRC flow at GC [1]	28	6.1	0.1	0.23	2.2	2.6	7.4	0.383
GCUS	10	5.7	<0.05	0.05	0.5	3.14	0.3	0.057
GCMS -10m [2]	12	5.8	<0.05	0.08	0.8	2.96	1.3	0.105
GCMS +50m	12	5.9	0.05	0.12	0.7	3.02	0.9	0.093
GCDS	12	6.0	0.05	0.10	0.7	2.55	1.0	0.105

1 collected about 100 m before entering the creek;

2 10 m upstream from GCMS and 60 m upstream from 'GCMS+50m';

Note: Cd, Hg, Pb Th and Zn were close or below detection limits in all samples

Uranium concentration and uranium activity ratios ($^{234}U/^{238}U$) have been measured via alpha spectrometry, in order to identify activity ratios of possible contaminating endmember(s). The uranium activity ratio analysis of samples from the routine monitoring program focuses on samples collected during January to March 2004, February 2003 and February 2005.

Some difficulty in the iron oxide precipitation step as described in Martin and Hancock (2004) was encountered resulting in low uranium recoveries. A slightly modified procedure provided the recovery and peak resolution required for uranium isotope ratio analysis. The effect of the sample matrix of Gulungul Creek waters is being investigated further by analysing spiked samples.

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Part 2: Ranger – Rehabilitation

Contents[1]

[1] List of papers grouped by Key Knowledge Need.

KKN 2.2.4 Radiation exposure pathways associated with ecosystem establishment

2.5 Monitoring

KKN 2.5.1 Monitoring of the rehabilitated landform

KKN 2.5.2 Off-site monitoring during and following rehabilitation

Reliability assessment of Siberia model outputs

KG Evans & GR Willgoose[1]

Introduction

Several research projects have been completed addressing the application of the Siberia landform evolution model (LEM) to mine site rehabilitated landform design. These projects include derivation of site input parameters (Evans et al 1998, Willgoose & Riley 1998), validation of the model (Hancock et al 2000, 2002), assessment of temporal trends in landform development (Moliere et al 2002) and development of a GIS front-end (Boggs et al 2001).

During the assessment of impacts of uranium mining on Kakadu National Park by the Independent Scientific Panel (ISP), the error bounds/uncertainties in model simulations were questioned. This project was established with Professor G Willgoose, the author of Siberia, to address these questions.

This reliability assessment project comprised four stages: 1) Project design and input errors for quantitative reliability assessment (QRA); 2) Characterisation of errors; 3) Modification of Siberia and associated software; and 4) Risk assessment modelling.

Progress to date

Stages 1 and 2 are complete and reported in the Project Design Document (PDD) (Willgoose 2005).

Stage 1 defined the following model input errors:

- **Uncertain temporal trends:** These are processes, which evolve systematically through time e.g. the grading of an erosion surface to a stable armour.
- **Random temporal events:** These are events that occur randomly with time e.g. rainfall, fire.
- **Uncertain spatial trends, patterns and organisation:** These are properties that vary in space systematically e.g. variation in spoil characteristics due to random dumping.
- **Random spatial effects:** Properties that have spatial variation such as waste rock dump settlement.
- **Model fitting uncertainty:** This is the scatter of data around a best fit in a scatter plot. This scatter generally arises from two sources: (a) model error i.e. the inability to simulate the observed physics, (b) observation error i.e. the inability to correctly measure the observed physics.

The possible sources of error to be considered in LEM predictions are:

- **Climate:** (a) reliability of longterm rainfall record and is representativeness of the actual longterm averages and extremes; (b) the possible effect of extreme events; and (c) the effect of rainfall on vegetation cover and erosion.

[1] Telluric Research,100 Barton Street, Scone, 2337 Australia.

- **Hydrology:** (a) effect of surface roughness on runoff-routing; (b) infiltration properties; and (c) spatial correlation of rainfall on the area-scaling effect.
- **Sediment transport:** (a) temporal and spatial variability of material fluvial erodibility and discharge and slope dependence of fluvial sediment transport; and (b) the effect of ignoring creep/rainsplash diffusion transport.
- **Vegetation:** (a) linkage of vegetation density to climate variability; (b) fire effects; (c) spatial variation of vegetation density.
- **Waste rock dump:** The effects of waste rock dump settlement and tailings consolidation on drainage patterns and incision.
- **Siberia algorithms:** The ways in which Siberia approximates the physics of the system: (a) grid elevation discretisation and algorithms for drainage analysis; and (b) grid discretisation resolution, orientation and origin.

Stage 2 is the characterisation of errors and the PDD (Willgoose 2005) outlines methodologies for characterisation of errors. This will not involve additional data collection beyond what has been completed or currently in progress by ***eriss***.

Stages 3 and 4 involves Monte-Carlo simulations and risk assessment. Further project development is currently underway.

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Assessing the geomorphic stability of the currently proposed final landform at the Ranger mine using landform evolution modelling

JBC Lowry & KG Evans

Introduction

The environmental requirements for mine closure at the Ranger Mine in the Northern Territory specify that the mine landscape must be rehabilitated such that the final landform and composition of the plant communities are compatible with those of the surrounding areas of Kakadu National Park.

A draft landform design was created based on the 2001 life of mine plan, and evaluated using the SIBERIA landform evolution model and ArcView GIS software packages which had been integrated through an interface known as ArcEvolve (Boggs 2003). Siberia uses a series of hydrology and erosion parameters to model long-term changes in elevation with time from the average effect of mass transport processes, such as tectonic uplift, fluvial erosion, creep, rainsplash and landsliding. The input parameters are applied to a series of 'regions' which represent different surface conditions over the landform being modelled. For the purposes of evaluation, surface conditions representing best and worst case scenarios were modelled. Using the hydrological parameters for natural surface conditions and rock / batter surface conditions, it is possible to simulate different scenarios for the evolution of the proposed landform for periods of up to 1000 years.

The evaluation highlighted areas of the draft landform that needed to be redesigned to match analogue specifications and to reduce gully erosion.

Progress to date

Using the methodology described in Lowry et al (2004), the draft landform was modelled for a period of 1000 years, with hydrology parameters held constant for the entire landform and erosion parameters varied for each region of the landform representing different surface treatments. Through the GIS interface, it was possible to identify areas of potential erosion/deposition by subtracting the 1000-year modelled surface from the current surface (figure 1).

The version 3 landform supplied by EWLS has been evaluated by Siberia using the ArcEvolve Siberia interface. The results of the modelling identified areas on the draft landform which needed to be redesigned, in order to minimise erosion from the landform. As indicated by the box in figure 1, a gully with a maximum depth of up to 14 metres was predicted to form on the left side of Pit 3 over a period of 1000 years, with the size and extent of the gully varying for the different scenarios.

Whilst recognising limitations with the modelling process, such as the inability to incorporate the different hydrology characteristics associated with different surface conditions on the landform within the model, the current process is able to perform distributed erosion modelling. This has enabled 'best case' and 'worst case' scenarios to be modelled with confidence within a range of erosion and deposition parameters.

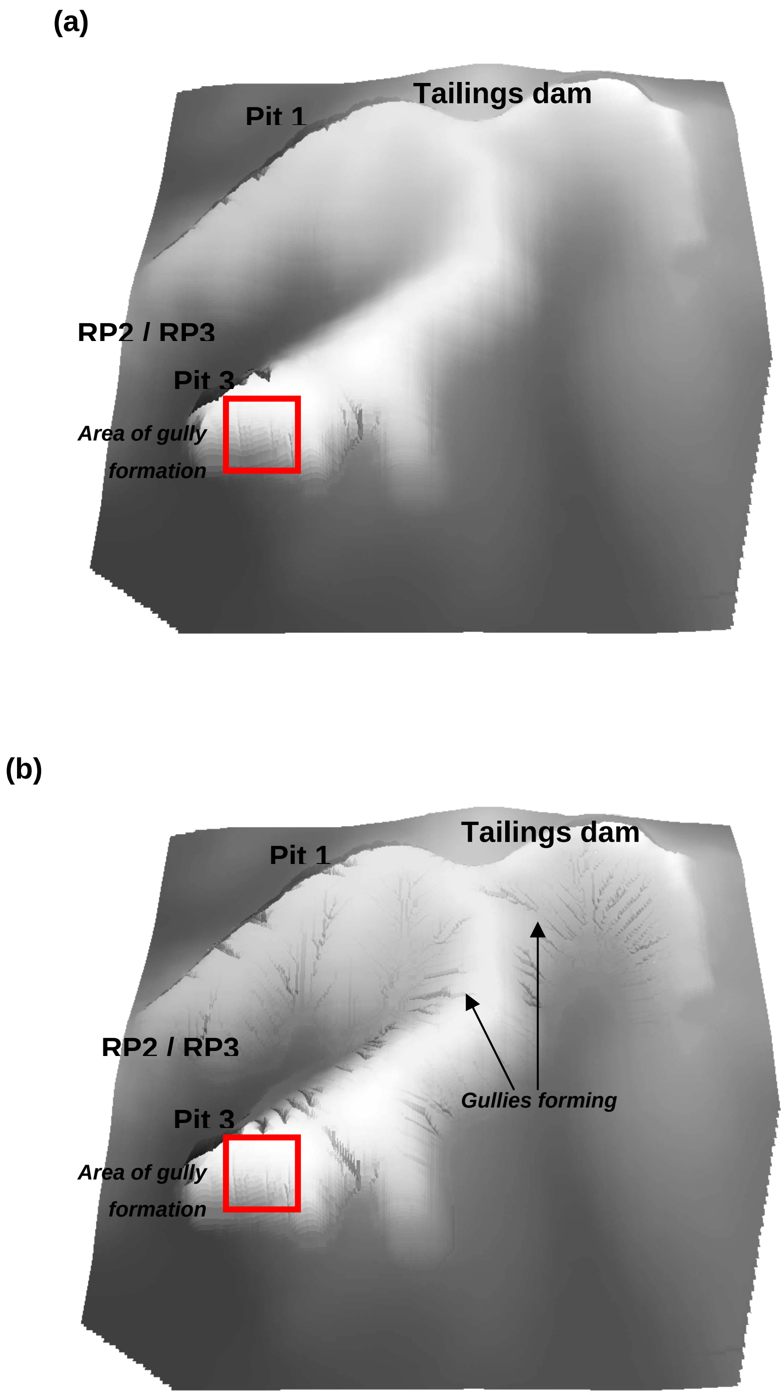

Figure 1 Areas of potential erosion / deposition (illustrated by gullies forming on slopes) on v3 landform using parameters for (a) 'best case' scenario; and (b) 'worst case' scenario

Simulated surface denudation rates (table 1) were calculated using ArcEvolve, and found to compare favourably with regional denudation rates of 0.04 mm/y for natural undisturbed surfaces (Cull et al 1992).

Table 1 Predicted denudation rates on the Ranger landform

Landform	'Best case' denudation rate (mm/yr)	'Worst case' denudation rate (mm/yr)
1000-year modelled with natural hydrology parameter	0.02	0.06

A draft report has been jointly prepared by EWLS and SSD describing the results of the modelling of the initial landform. In addition, the results of the modelling have been jointly presented by EWLS and SSD in a paper at the NARGIS (North Australian Remote Sensing and GIS) conference in Darwin (4–7 July 2005).

For the 2005–06 work program, the project will evaluate the final landform design proposed by EWLS. It will also ascertain whether current problems in incorporating hydrological parameters into Siberia are a result of a problem within the GIS interface or the Siberia program itself.

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Radio- and lead isotopes in sediments of the Alligator Rivers Region

A Bollhöfer & A Frostick[1]

Introduction

The aims of this project are to develop an innovative, sensitive and cost-effective methodology to assess and monitor impacts of past, present and future uranium mining activities in the Alligator Rivers Region. A combination of stable lead isotopes, trace metals and radionuclide techniques is used and concentrations are measured in both surface scrapes and sediment cores, to determine the sediment deposition history and extent of erosion and pollution in potentially mining influenced catchments. A pilot study conducted in the Ngarradj catchment (Bollhöfer & Martin 2003) outlines the general approach. The project is funded through the Australian Research Council (ARC) Linkage-Projects scheme and is conducted in collaboration with Charles Darwin University (CDU).

Ranger studies indicate that lead isotope ratios are an ideal source tracer to identify uranium rich solids. Lead isotope ratios are highly radiogenic as shown in a study of airborne dust originating from Ranger (Bollhöfer et al 2005) and measurements of particulates in tailings dam water (Gulson et al 1996). Coupled with the measurement of radionuclide and heavy metal concentrations, past and present erosion and subsequent deposition of contaminants originating from mining activities or unstable landforms may be identified and quantified. Koongarra and the Nourlangie Creek catchment may act as a natural analogue in this regard.

Method

The following 4 catchments will be investigated.

- Rehabilitated Nabarlek mine and the Cooper Creek catchment
- Ranger mine and the Magela and Gulungul Creek catchments
- Jabiluka and the Ngarradj catchment
- Koongarra and the Nourlangie Creek catchment.

Surface scrape and sediment core samples are collected during the early dry season. Core samples are then sliced into 1–2 cm samples and prepared for measurement via ICP-MS for heavy metals and lead isotope ratios (Munksgaard et al 2003). Samples will then be combined for gamma analyses at ***eriss*** for U and Th-series elements, following standard procedures (Marten 1992). Cs-137 will also be measured in an attempt to obtain a chronology for the sediment cores.

[1] Charles Darwin University, Darwin NT.

Results

Soil scrapes and sediments from and adjacent to the Nabarlek mine site were collected in 2004 and 2005. Soil scrapes indicate that radiogenic material is deposited along major drainage lines, which may originate from the radiological anomalous area (RAA), or unit-7, just south of the former pit (figure 1). A former erosion assessment using the Revised Universal Soil Loss Eqaution (RUSLE) estimated that this area produces 74% of the total ^{238}U flux (and 84% of the total ^{226}Ra flux) to the Cooper Creek system, despite it having a relatively small surface area (Hancock et al 2006).

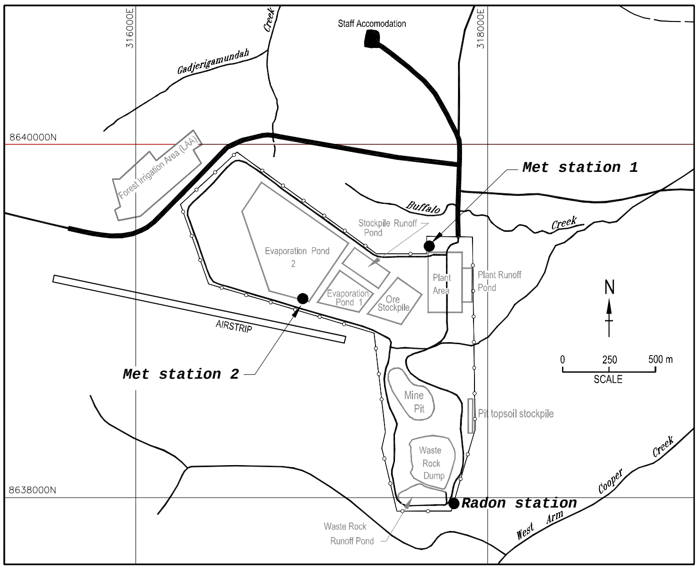

Figure 1 The rehabilitated Nabarlek mine and major features on site

Figure 2 shows lead isotope data measured in the samples from Nabarlek, together with data from a recent study of lead isotopic signatures in dust around Ranger uranium mine (Bollhöfer et al 2005) and results from samples taken in creek beds of the Ngarradj catchment (Bollhöfer & Martin 2003). Scrape samples taken from the Radiological Anomalous Area (RAA) exhibit even more radiogenic lead isotope ratios than those measured in Ranger uranium mineralised material, with higher $^{206}Pb/^{207}Pb$ and $^{208}Pb/^{207}Pb$ ratios. Consequently, the samples collected at Nabarlek clearly follow a trend with a different endmember as the one observed in Ranger studies.

To determine the extent of erosion and deposition at Nabarlek, six sediment cores in backflow deposition zones along Cooper Creek, upstream and downstream of the mine site, have been collected in June 2005 and a further three cores from Kadjirrikamarnda Creek. Lead isotope results of Cooper Creek Core 9 downstream of Nabarlek but upstream of the Kadjirrikamarnda Creek confluence, are shown in figure 2 as well. The core samples follow a trend similar to the trend observed in Ngarradj sediments, exhibiting a mixture of relatively thorium rich sands at the bottom of the core with natural clays and organics at the top, and seem to be relatively unaffected by radiogenic lead.

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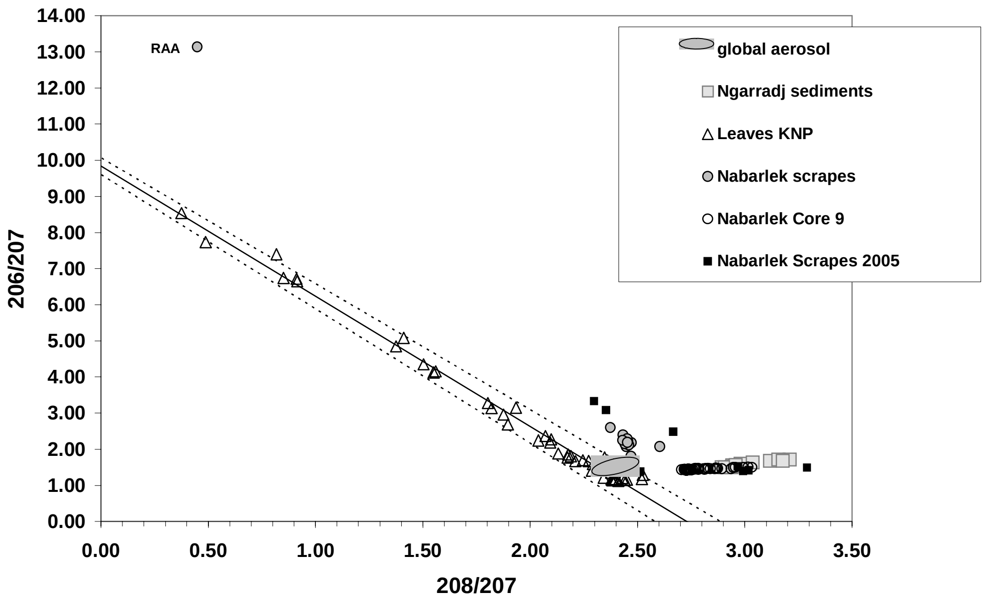

Figure 2 Three isotope plot of sediment samples taken at Nabarlek and Ngarradj and dust samples in the Ranger region

Radon exhalation at and around Ranger uranium mine

C Lawrence[1], R Akber[2], P Martin[3] & A Bollhöfer

Introduction

Airborne dispersion of radon and the subsequent inhalation of radon progeny is the major pathway of exposure of the public to natural sources of ionising radiation. UNSCEAR (2000) reported that radon isotopes contribute to more than 50% of the natural source of radiation exposure and measurements have shown that a dose of approximately 0.7 milliSievert (mSv) per annum is received in Jabiru due to the inhalation of radon progeny. However, it is necessary to distinguish natural and Ranger derived radon. Estimates for the mine-origin radon exposure range from less than 0.01 (Martin 2000) to more than 0.2 mSv per year (Kvasnicka 1990) at Jabiru.

In order to reliably model radon-222 (^{222}Rn) concentrations in air following rehabilitation it is necessary to know the ^{222}Rn exhalation source term in the Ranger area. This work was carried out in collaboration with Queensland University of Technology to determine the current source term and its temporal variation, and to develop algorithms that describe ^{222}Rn exhalation in terms of key soil characteristics. The information will be used to predict ^{222}Rn exhalation from the site after rehabilitation. The work program consisted of three main parts:

- Measurements of ^{222}Rn exhalation from surfaces at Ranger during the dry season;
- Measurements of ^{222}Rn exhalation at various sites over a seasonal cycle;
- Measurements of ^{222}Rn exhalation at various sites over several diurnal cycles.

Methods

A total of 654 readings of ^{222}Rn flux density were obtained in dry season conditions. Of these 298 were obtained from pit 3, pit 1, ore stockpile grade 2, ore stockpile grade 7, waste rock dump, overburden, laterite stockpile and irrigated and non-irrigated sections of the Magela land application area.

^{222}Rn flux densities were measured using two methods: activated charcoal canisters and scintillation emanometers. After retrieval, charcoal canisters were stored for an ingrowth period of at least four hours to allow for the establishment of equilibrium between ^{222}Rn and its progeny. The activity of ^{222}Rn adsorbed on the charcoal was then determined by counting on a portable gamma spectrometer with a 3” x 3” NaI(Tl) crystal housed in a lead castle.

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[1] Formerly SSD ; now ERA Ranger Mine, Jabiru NT.

[2] Queensland University of Technology, Brisbane Qld.

[3] Formerly SSD; now Agency’s Laboratories Seibersdorf, IAEA, A-1400, Vienna, Austria.

Results

^{222}Rn flux densities were highest for the ore stockpiles with fluxes from the laterite stockpile being three orders of magnitude larger than from environmental areas, which are typically 70 milliBecquerels per m^2 per second (mBq·m^{-2}·s^{-1}). ^{222}Rn flux densities from the waste rock dumps and the pits are 1–2 orders of magnitude higher, whereas those from the irrigated land application area were only slightly higher than the environmental areas at 112 mBq·m^{-2}·s^{-1}.

Radon exhalation from soils is influenced by a variety of factors, such as soil moisture, soil porosity and soil radium-226 (^{226}Ra) content. As measurements were conducted over the dry season, we were able to investigate the dependency of the ^{222}Rn flux density on soil ^{226}Ra content and soil porosity. Figure 1 shows the ^{222}Rn flux density plotted versus the soil ^{226}Ra content for various geomorphic groups: barren (disturbed) areas where compaction has taken place as a result of human influence, vegetated woodland and rehabilitated sites with relatively porous vegetated soils, non-compacted fine grains such as the laterite push zone or overburden zones, and non-compacted boulders. Compaction of the ground and reduction of soil porosity decrease radon exhalation whereas vegetation with established root structures leads to higher exhalation fluxes.

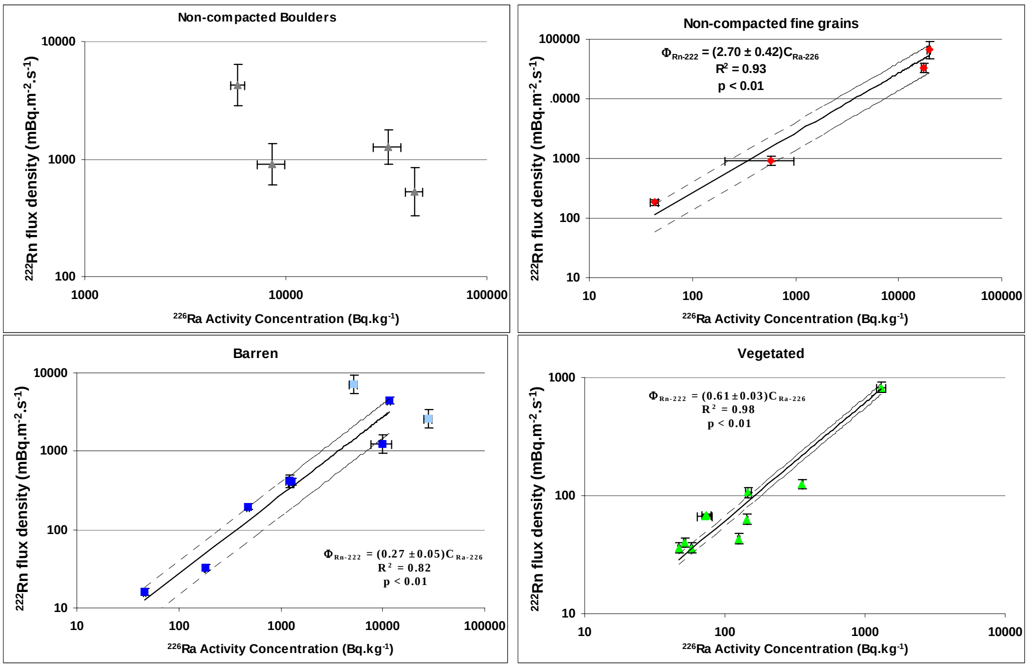

Figure 1 ^{222}Rn flux density plotted versus the soil ^{226}Ra content for various sites

Seasonal measurements of radon exhalation

^{222}Rn flux density measurements were performed over the course of one year at eight sites in the region. Previous studies have indicated that there are large variations in flux between wet and dry season in northern Australia. The influence of soil moisture is the most likely reason for this. Soil moisture profiles (0–1 m) were determined in conjunction with every set of flux measurements at some seasonal sites. The soil moisture data showed large temporal variations throughout the wet season which explains the large variations of ^{222}Rn flux densities during the wet.

Figure 2 shows the annual variation of ^{222}Rn flux densities at four of the eight investigated sites, and the cumulative rainfall during the time. Generally, radon exhalation in the wet season was largely reduced as soil moisture retarded radon exhalation. However, localised variations were also observed. For instance, some of the sampling sites such as the Mudginberri radon station, Jabiru East or Mirray exhibited a peak in radon exhalation during charcoal cup exposure in January, which is likely to be due to evaporation of soil water and the release of trapped radon after a short but intense rain event.

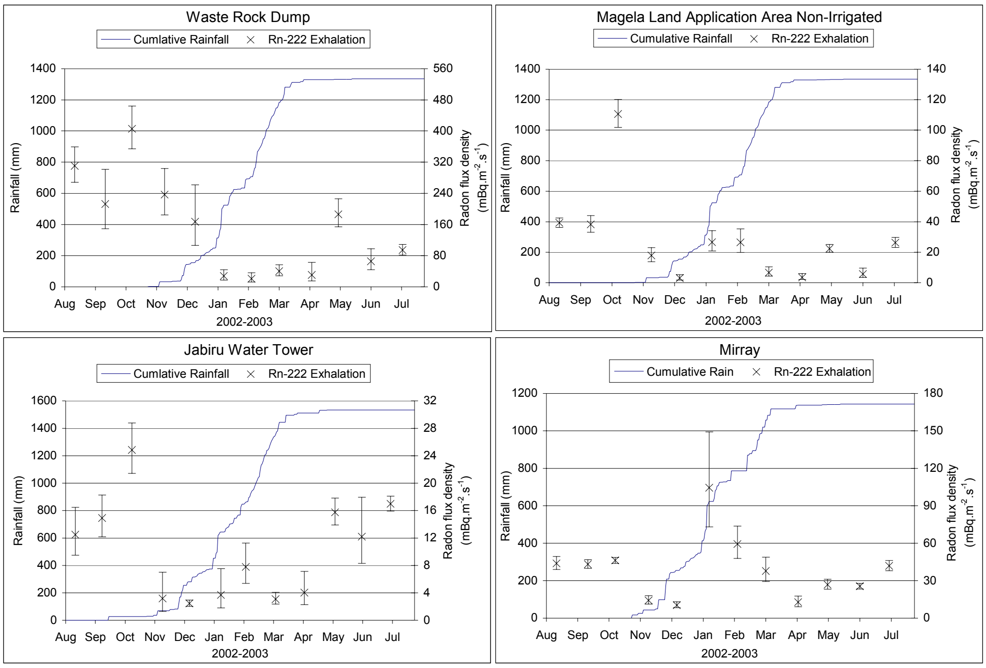

Figure 2 Annual variation of ^{222}Rn flux density and cumulative rainfall plotted versus the date

Diurnal measurements of radon exhalation

The aim of this part of the study was to establish whether there was a correlation between radon exhalation, time of day and meteorological parameters such as atmospheric pressure, site and soil temperature. Diurnal measurements were performed at five of the seasonal sites. To investigate whether diurnal radon flux density variations were dependent upon the soil moisture content, measurements were performed during the wet season and during the dry. The results indicate that there is little or no diurnal variation of ^{222}Rn flux density and that a correlation with soil temperature and atmospheric pressure, if any, is masked by random variations of radon exhalation and measurement uncertainty.

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Development of predictive habitat suitability models of vegetation communities associated with the rehabilitated Ranger final landform

C Humphrey, I Hollingsworth[1] & G Fox

Background

Target plant and animal communities must be identified and characterised for a number of sites and ecosystem types following Ranger mine-site rehabilitation, including the final, post-mine landform. Monitoring of target communities will then be required at these sites to assess the extent to which rehabilitation is being successfully sustained and achieved.

For vegetation communities, Hollingsworth et al (2003) identified natural analogue areas similar in size, underlying geology and conformation to a draft Ranger final landform design and representing the local range of habitats and ecosystem diversity in the lowland, Koolpinyah land surface. Hollingsworth and Meek (2003) made a detailed survey of plant communities in one of these analogue areas, the Georgetown area to develop criteria for ecosystem reconstruction.

The Georgetown analogue area is adjacent to and south-east of the Ranger mine (figure 1B). The authors related six ecosystem types identified from multivariate classification methods to key geomorphic features (parent material, slope, effective soil depth etc). Such relationships are essential in identifying sustainable and achievable 'landscape' analogues (or target habitats) for the final, post-mine landform at Ranger (Reddell & Meek 2004).

In a critique of the analogue work of Hollingsworth et al (2003), Dr Carl Grant, independent member of ARRTC, recommended: (i) that the study be expanded beyond the current narrow geographic extent to the broader environment of Kakadu National Park; and (ii) that the vegetation classification incorporates species abundance data (hence, aligned better to the broader rehabilitation objectives set for Ranger for which plant density must be considered) (ARRTC request 3H from the 13th meeting March 2004, redo vegetation classification to consider species abundance.) Reddell and Meek (2004) also noted that this initial EWLS work may need to be extended by way of additional surveys, to 'refine some of the target vegetation types once the design features of the final landform are finalised (eg for drainage lines, or for potentially waterlogged areas such as the former tailings dam floor)'.

In this current project, vegetation survey data previously obtained by ***eriss*** across a broad geographical range and broad landform types throughout the ARR (Brennan 2005) have been combined with the EWLS Georgetown analogue data, in accordance with the above recommendations. The aim of the project is to (i) use this extended analysis to re-classify and characterise plant communities; and (ii) from plant community-environment relationships, derive predictive models based upon physical and chemical input variables. The derived, target plant communities may then be considered as the basis of revegetation and post-rehabilitation monitoring programs.

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[1] Earth, Water, Life Sciences, Darwin NT

The objectives of Brennan's (2005) study, data for which were gathered in the early 1990s, were also based upon Ranger final landform-analogue analysis. The objectives of his study were twofold:

1 To obtain quantitative data from undisturbed native plant communities in areas adjacent to the Ranger uranium mine site that may be considered useful as models for future revegetation strategies and standards.

2 Acknowledging that sites from 1. may not necessarily be useful analogues of the final landform (considering substrate, aspect etc), to describe undisturbed native vegetation on a range of sites elsewhere in the ARR where the topography and/or substrates were perceived to be more similar to conditions expected to prevail on the Ranger waste rock dump. 'Comparison of vegetation communities on these sites with those adjacent to the WRD could indicate the degree to which adjacent vegetation might be useful as a model for revegetating the Ranger WRD' (Brennan 2005).

This progress report:

- provides summary results of some multivariate analyses, including classification and plant association analysis, performed on combined eriss and EWLS plant community datasets; and
- considers some key issues to be considered in progressing this plant analogue study further.

More complete reporting of results of this study are provided in Humphrey et al (2006), including additional methods descriptions and multivariate analyses, and tabulation of the full plant datasets.

Multivariate analyses

Methods

Survey sites

Quantitative plant community data were gathered by Brennan (2005) over the period 1991 to 1993, from 20 potential analogue sites (figure 1):

- 10 well-drained lowland sites, on low, broad ridges adjacent to Ranger, and on the weathered Koolpinyah surface (amongst the 'Ranger sites' in figure 1A and designated 'R' in figure 1B);
- five sites on weathered hills composed of Cahill formation schists: four at Tin Camp Creek and 1 at Fisher (figure 1A); and
- five sites on sandstone (four sites) and quartzite (one site Mt Cahill) hills (figure 1A).

Similar quantitative plant community data were gathered by Hollingsworth and Meek (2003) from 18 sites in the Georgetown analogue area, adjacent to and south-east of the Ranger mine – figure 1B. These sites are located on the weathered Koolpinyah surface, though unlike comparable sites of Brennan's (2005), site selection was deliberately broad, encompassing rocky outcrops, slopes and crests, stream alluvium and poorly-drained flats.

Data analysis

'Trees and shrubs' data for the 38 collective sites of EWLS and ***eriss*** described above were combined (species density per hectare). (Herb data are available from both sources but have not yet been examined.) Brennan (2005) and Hollingsworth and Meek (2003) classified 'trees and shrubs' as >1.5 m and >2 m respectively. This size class difference is regarded here as sufficiently small that it would not lead to any significant artefacts in data pooling. Other consequences of pooling of the two datasets are described in Humphrey et al (2006). Two data transformations were applied to data analysis: log (x+1) and presence-absence.

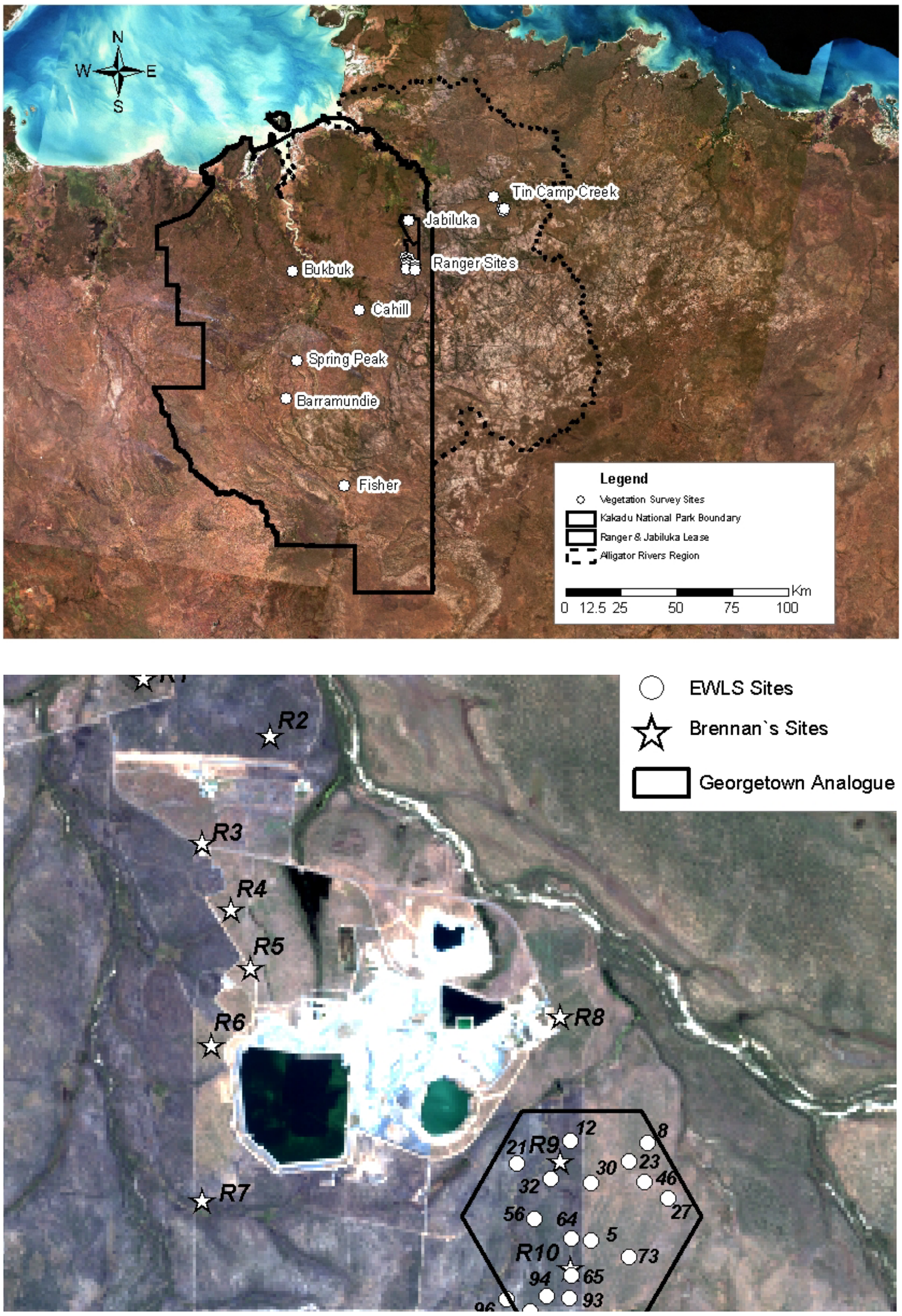

Figure 1 Maps of plant analogue sites surveyed by Brennan (2005) (A and B) and EWLS (Hollingsworth et al 2003) (B)

Plant community data were analysed using multivariate procedures from the PRIMER (v5) software package (Clarke & Gorley 2001). Three levels of analysis were applied:

1 Describing pattern amongst the assemblage data using cluster (classification) and ordination techniques. The basis of these analyses was Bray-Curtis dissimilarity matrices. The clustering technique used a hierarchical agglomerative method where samples of

similar assemblages are grouped and the groups themselves form clusters at lower levels of dissimilarity. A group average linkage was used to derive the resultant dendrogram. The ordination method used was Multi-Dimensionsal Scaling (MDS) (Clarke & Warwick 2001). Ordinations were depicted as two-dimensional plots based on the site by site dissimilarity matrices.

2 For the *a priori* factor, landform type (comprising three groups, Koolpinyah lowlands, schist hills and sandstone hills), Analysis of Similarity (ANOSIM) – effectively an analogue of the univariate ANOVA – was conducted to determine if the group comparisons were significantly different from one another. The ANOSIM test statistic reflects the observed differences *between* groups (landform types) with the differences amongst replicates *within* the groups. The test is based upon rank dissimilarities between samples in the underlying Bray-Curtis dissimilarity matrix.

3 The SIMPER routine was used to examine which plant species were contributing to the differences of landform groups that were found to be different according to the ANOSIM procedure. For visualisation, the numeric value of some key plant species were superimposed onto plant density MDS ordinations, as circles of differing sizes – so-called 'bubble plots'.

Results

Pattern analysis (classification and ordination)

Cluster analysis of plant community data showed similar groupings for both density and presence-absence data (figure 2). At a relatively high level of dissimilarity (~75% for density data and ~65% for presence-absence data), five groups were identified. For density data, the hill sites of Brennan (2005) were dispersed across three of these groups while EWLS sites were dispersed across four of the groups (figure 4).

In ordination space, for both density and presence-absence data, hill sites of Brennan's (2005) were located to one (right-hand) side of Axis 1 of the ordination, while his and the EWLS lowland Koolpinyah sites were generally dispersed across the other (left-hand) side of Axis 1 of the ordination (figure 3).

EWLS sites were well dispersed in ordination space and amongst classification groups. This spread is much greater than Brennan's (2005) equivalent lowland sites, even though the EWLS sites are much more geographically constrained than Brennan's. This indicates the EWLS analogue location has captured a greater variety of landform types, borne out in the study designs of both studies where Brennan's Koolpinyah sites were deliberately confined to low, broad ridges while the comparable EWLS sites were selected from across a range of landforms. Nevertheless, the EWLS sites do not appear to capture well 'hill' flora (figure 3).

In general, the groups identified from cluster analysis do not separate according to the broad *a priori* landform types based upon substrate and topography (figure 4). While axis 1 of the corresponding plant density ordination distinguishes hills and lowland vegetation communities, the two largest cluster groups cut across both ordination axes, each capturing hills and lowland vegetation sites (figure 4). To some extent, the ordinations and classifications may be influenced by plant density and species richness (number) *per se*. Thus Axis 2 of the ordinations appears to be correlated with increasing plant density and species richness (figure 5).

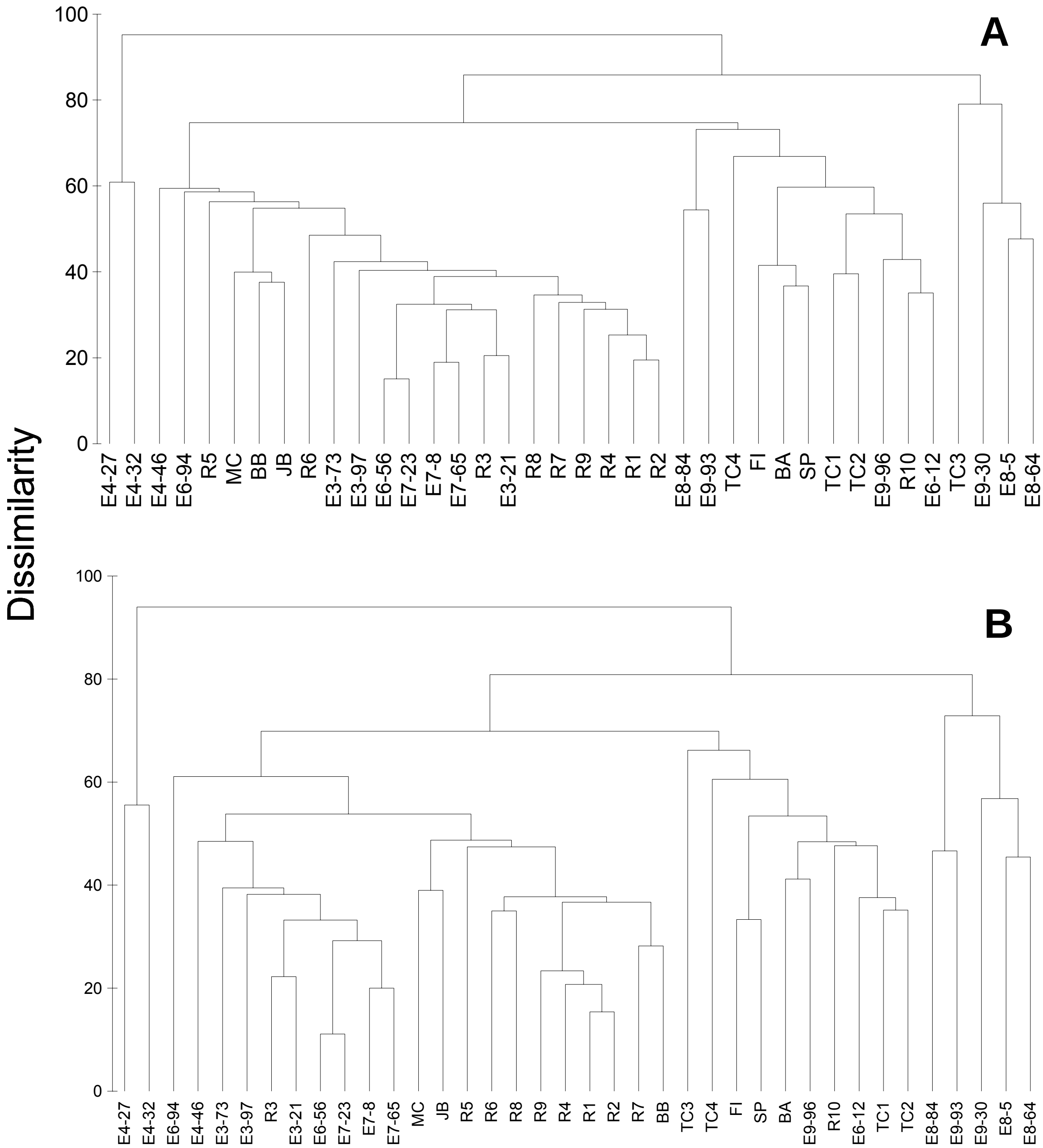

Figure 2 Cluster analysis (group average linkage) of combined ERISS and EWLS 'trees and shrubs' data from different ARR landforms. Data for A are log transformed density/hectare units, data for B are presence-absence.

Key to site codes:
'E' sites = Hollingsworth et al (2003) Georgetown analogue site,
'R' sites = Brennan's (2005) lowland Koolpinyah sites around Ranger
'TC' (Tin Camp Creek) and 'F1' (Fisher) = schist hills
JB, BB, BA, SP = sandstone hills
MC = quartzite hill

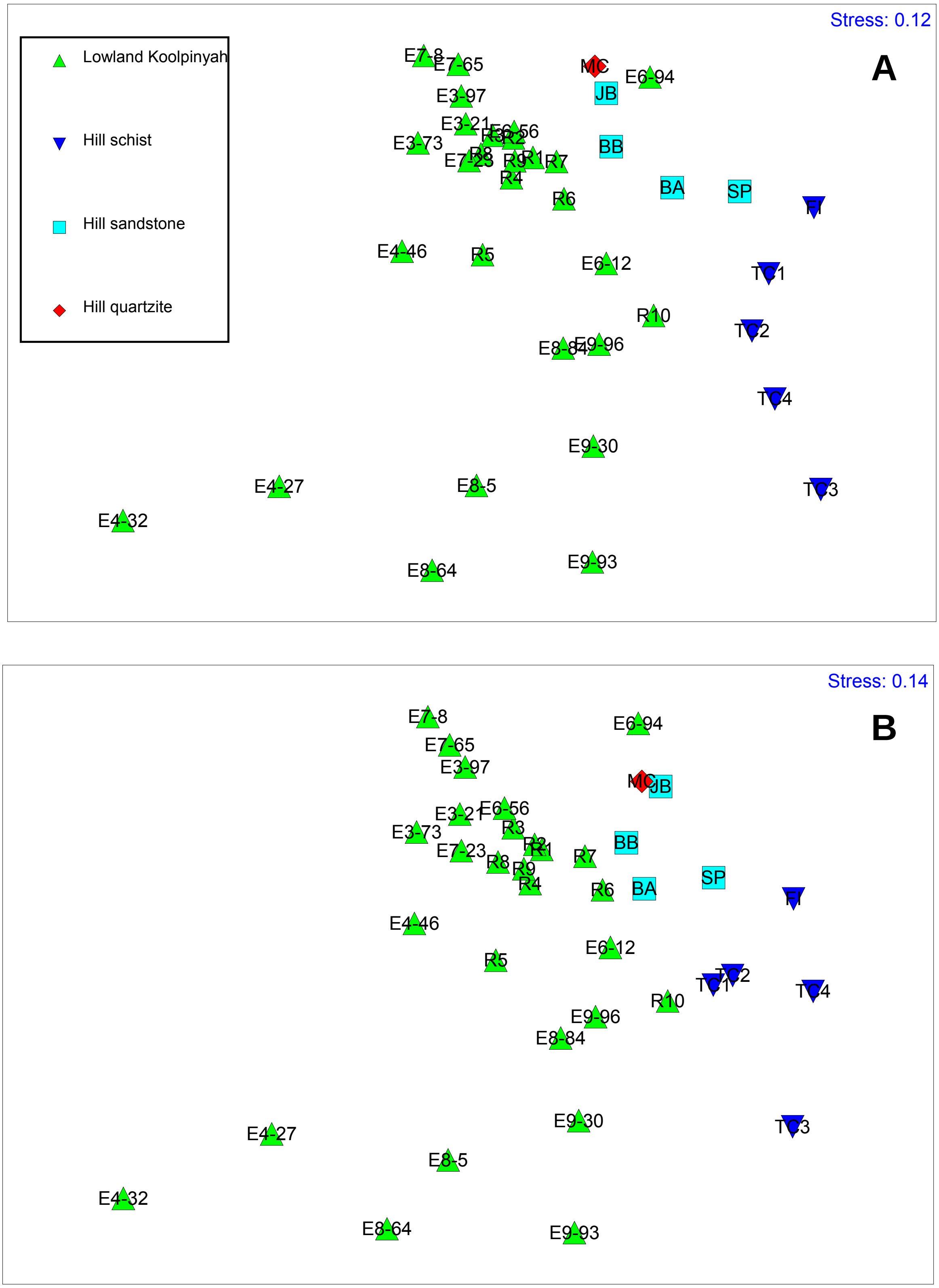

Figure 3 MDS ordination of combined ERISS and EWLS ‘trees and shrubs’ data from different ARR landforms. Data for A are log transformed density/hectare units, data for B are presence-absence. General key to site codes is provided in figure 2.

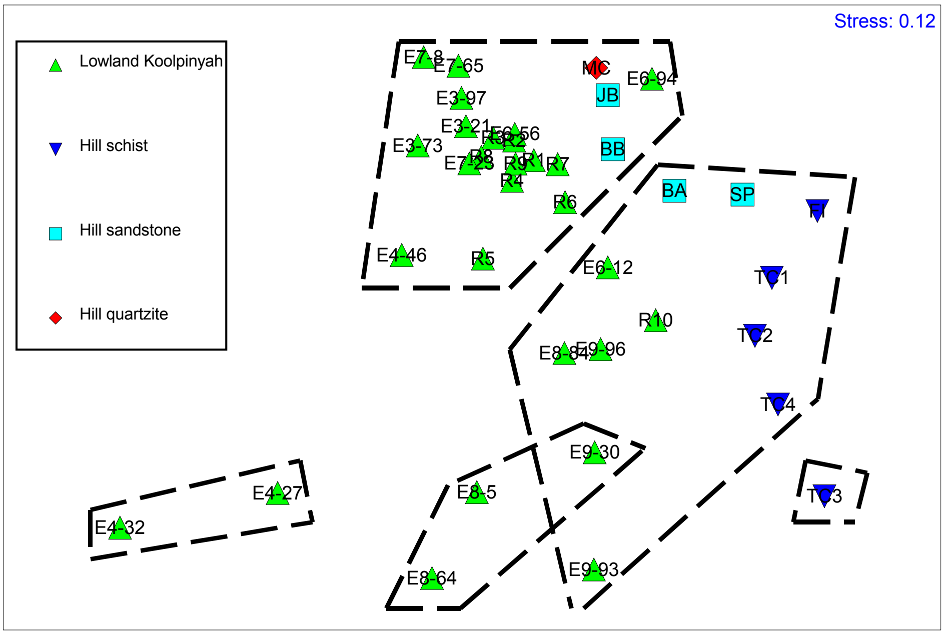

Figure 4 MDS ordination of combined ERISS and EWLS 'trees and shrubs' density data from different ARR landforms, overlain by groupings identified from (plant density-derived) cluster analysis (from figure 2). General key to site codes is provided in figure 2.

Analysis of Similarity (ANOSIM)

Results for ANOSIM, performed on the *a priori* groups sandstone hills, schist hills and Koolpinyah lowlands, are shown in table 1 according to plant density and presence-absence data. Significance levels for the global test are low (~5%) indicating significant group, pairwise differences somewhere amongst the landform comparisons. The important statistic to observe for the pairwise comparisons (table 1) is not so much the significance level (which is sensitive to sample size, in this case sites within a landform), but the pairwise R values. The table caption of table 1 provides some 'rules of thumb' in interpreting R values. For both plant density and presence-absence data, there is significant separation between lowland Koolpinyah and schist hill sites, and between schist hill and sandstone hill sites (table 1).

Table 1 ANOSIM on factor landform type, giving the significance of the test, with degree of separation between groups (R-statistic), where R-statistic >0.75 = groups well separated, R-statistic >0.5 = groups overlapping but clearly different, and R-statistic <0.25 = groups barely separable. A significance level <5% = significant effect/difference.

Groups	R Statistic	Significance level (%)
Species presence-absence data		
Sample statistic (Global R) = 0.196; Significance level of sample statistic: 5.3%		
Lowland Koolpinyah, Hill schist	0.376	1
Lowland Koolpinyah, Hill sandstone	0.014	44.2
Hill schist, Hill sandstone	0.484	1.6
Species density data		
Sample statistic (Global R) = 0.196; Significance level of sample statistic: 5.3%		
Lowland Koolpinyah, Hill schist	0.455	0.5
Lowland Koolpinyah, Hill sandstone	0.082	29.7
Hill schist, Hill sandstone	0.463	1.6

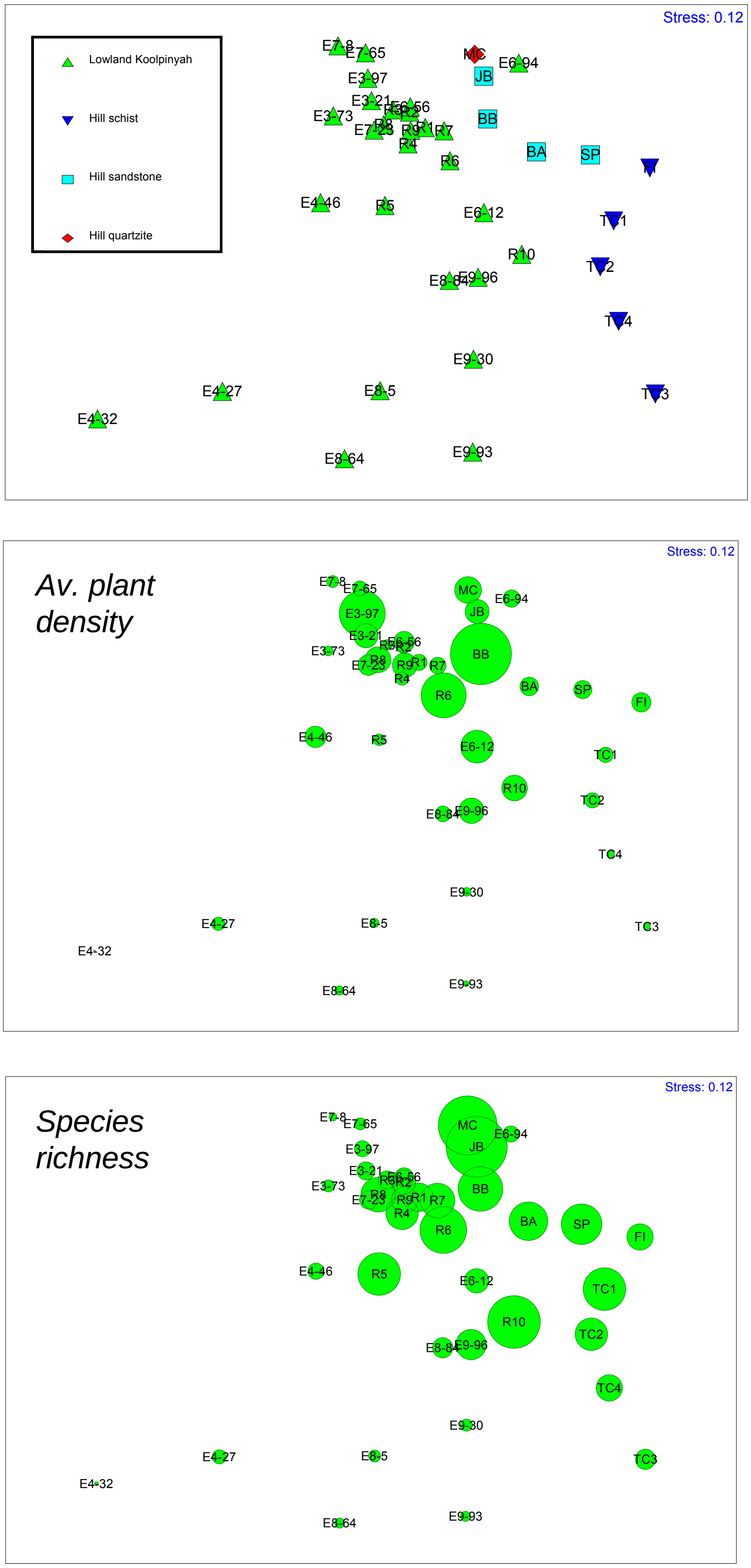

Figure 5 MDS ordination of plant density data, with bubble plots of average plant density and species richness (number)

Taxa contributing to the differences of site groups (SIMPER)

SIMPER analysis examines the plant species best representing and separating different multivariate groupings. SIMPER results are shown in tables 2 and 3 for the two landform comparisons, lowland Koolpinyah versus schist hill sites, and schist hill versus sandstone hill sites respectively. These two comparisons were shown to be significantly different in the ANOSIM analyses for both plant density and presence-absence data. Results are shown for plant density data (only) by way of (i) the average dissimilarity between all pairs of inter-landform samples, (ii) the dominant taxa, in decreasing order of importance, in contributing to the average dissimilarity between the two groups, and (iii) the cumulative percentage of overall dissimilarity contributed by the dominant taxa.

The average inter-landform dissimilarity was highest (= best group discrimination) for the lowland Koolpinyah versus schist hill sites comparison – 83% compared with the schist hill versus sandstone hill sites comparison – 70% (tables 2 and 3). The cumulative percentage of overall dissimilarity contributed by the dominant (say) 10-15 taxa is generally high (~50%) indicating that these taxa are contributing quite significantly to the landform differences. Some 'signature' dominant plants of sandstone versus schist substrates, identified from SIMPER analysis (tables 2 & 3), are plotted as 'bubbles' in figure 6.

Implications and possible future directions of analogue work

Brennan (2005) and other workers in the early 1990s regarded schist hills and associated landform responses (including runoff and infiltration characteristics) and resident biota as potentially suitable analogues for the future rehabilitated Ranger landform. (A reference list is provided in Humphrey et al (2006) of studies conducted by ***eriss*** and consultants at Tin Camp Creek analogue locations near Nabarlek.) In relation to the flora, Kym Brennan (pers comm) suggested the indicative flora of schist hills (tables 2 and 3), often with deciduous elements such as *E. tectifica*, was well suited to the heavy clay soils of these hills which do not allow deep root penetration. Ken Evans (pers comm) also notes the highly-resistant underlying metamorphic bedrock of ARR schist hills.

While the schist-hill-analogue hypothesis is potentially appealing, it also needs to be tested. It is questionable as to whether the Ranger final landform with its coarse rock fragments will present the same physical barrier to root penetration, even though surface armouring and a 'washed-in' layer of fine silt and clay will form (which itself could act as a barrier to root penetration of germinating seeds).

Workers at the Tin Camp Creek analogue sites in the early 1990s were mindful of the need to assess the edaphic features of analogue sites and hence affirm a basis for an analogue in terms of porosity and water movement/drainage, in addition to other soil properties including soil profiles, water availability and chemistry. However, it does not appear that the edaphic factors responsible for plant species composition have been sufficiently well investigated though much of the data required to do this may have already been gathered.

Table 2 SIMPER results for plant species discriminating pairs of analogue lowland Koolpinyah and Schist hill sites, based upon plant density data. Average dissimilarity between all pairs of inter-landform samples = 83%. Other key summary statistics are explained in the text.

Species	Lowland Koolpinyah Av.Abund	Schist Hill Av.Abund	Av. Dissim	Dissim/SD	Contrib'n%	Cumul.%
Acacia mimula	196.52	0.00	5.02	1.42	6.04	6.04
Eucalyptus tectifica	7.77	100.00	4.63	1.92	5.57	11.60
Calytrix achaeta	0.18	71.50	4.09	1.50	4.92	16.52
Eucalyptus tetrodonta	76.96	2.00	3.96	1.60	4.76	21.28
Xanthostemon paradoxus	110.18	10.00	3.90	1.32	4.69	25.97
Corymbia foelscheana	34.11	64.50	3.76	1.27	4.53	30.49
Cochlospermum fraseri	14.73	41.50	3.63	2.06	4.36	34.85
Erythrophleum chlorostachys	13.66	66.50	3.39	1.28	4.07	38.92
Corymbia porrecta	58.57	0.00	3.23	1.06	3.89	42.81
Grevillea decurrens	19.82	25.50	3.03	1.29	3.64	46.45
Eucalyptus pruinosa	0.00	48.00	2.80	0.72	3.36	49.82
Eucalyptus miniata	33.75	1.00	2.69	1.03	3.23	53.05
Hakea arborescens	9.20	12.50	2.52	1.15	3.03	56.08
Terminalia ferdinandiana	27.50	5.00	2.49	1.31	2.99	59.07
Planchonia careya	24.02	0.50	2.37	0.96	2.85	61.92
Buchanania obovata	5.80	13.00	2.34	1.10	2.81	64.73

Table 3 SIMPER results for plant species discriminating pairs of analogue schist hill and sandstone hill sites, based upon plant density data. Average dissimilarity between all pairs of inter-landform samples = 70%. Other key summary statistics are explained in the text.

Species	Schist Hill Av.Abund	Sandstone Hill Av.Abund	Av. Dissim	Dissim/SD	Contrib'n%	Cumul.%
Acacia mimula	0.00	112.50	3.41	2.61	4.86	4.86
Livistona humilis	0.00	48.75	3.21	2.33	4.58	9.44
Xanthostemon paradoxus	10.00	97.50	3.17	1.73	4.53	13.97
Eucalyptus tetrodonta	2.00	120.63	2.77	1.83	3.95	17.92
Corymbia foelscheana	64.50	0.00	2.74	1.39	3.91	21.83
Eucalyptus tectifica	100.00	4.38	2.53	1.68	3.61	25.44
Corymbia dichromophloia	37.00	50.63	2.41	1.01	3.44	28.88
Terminalia ferdinandiana	5.00	57.50	2.32	1.78	3.31	32.18
Erythrophleum chlorostachys	66.50	131.88	2.31	1.17	3.30	35.48
Eucalyptus miniata	1.00	28.75	2.25	1.67	3.20	38.68
Calytrix achaeta	71.50	26.88	2.12	1.40	3.02	41.70
Corymbia chartacea	16.50	94.38	2.10	1.00	2.99	44.69
Eucalyptus pruinosa	48.00	0.00	1.79	0.74	2.55	47.24
Livistona inermis	0.00	215.63	1.78	0.78	2.54	49.78
Croton arnhemicus	0.00	15.00	1.71	1.50	2.44	52.22

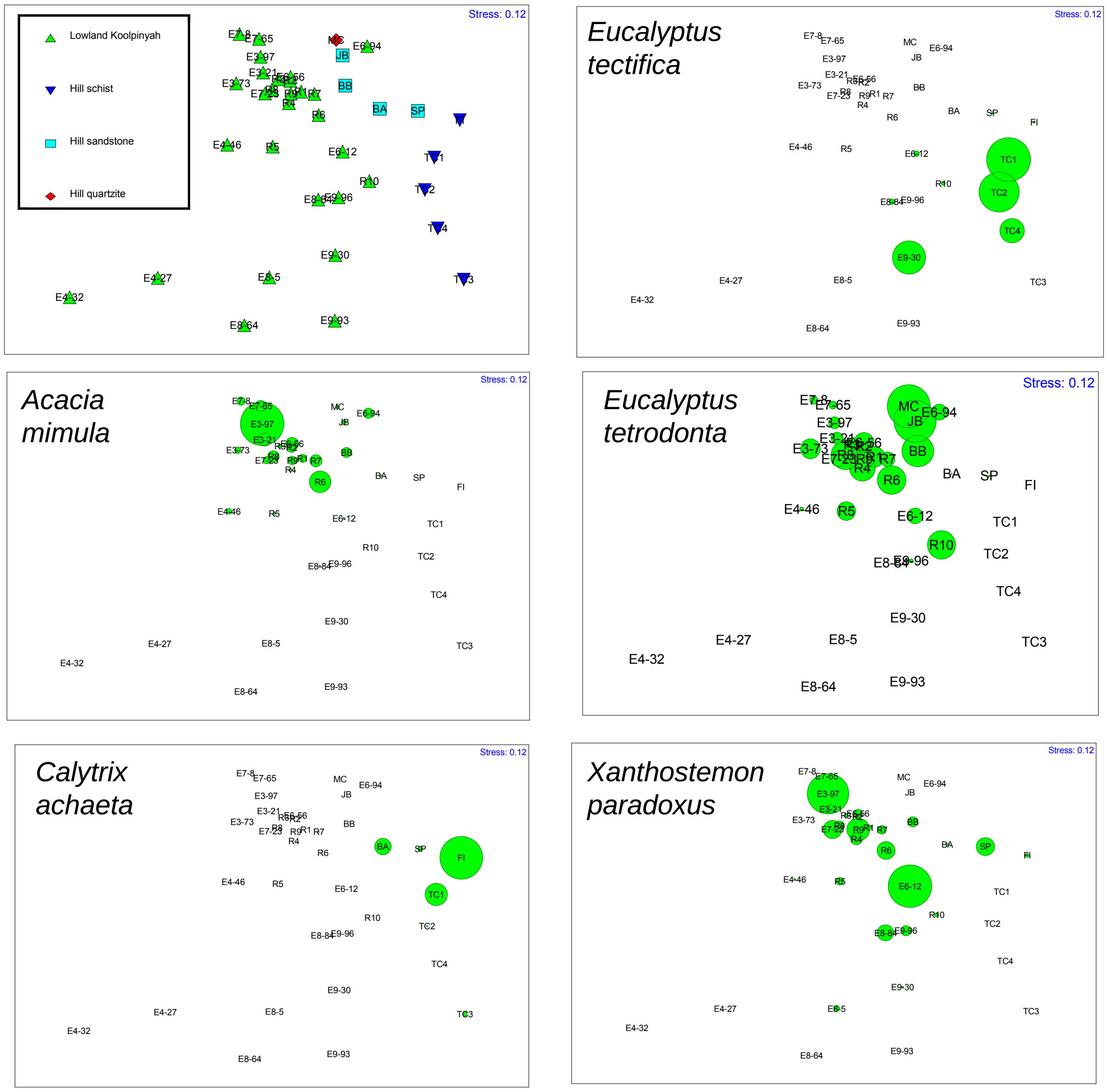

Figure 6 MDS ordination of plant density data, with bubble plots of key species identified by SIMPER as discriminating between schist and sandstone substrates

This objective of the ensuing study is to examine environmental relationships of the vegetation patterns found in the multivariate analyses performed to date. Anticipated components of the project are:

1 Review the ***eriss*** Tin Camp Creek analogue work and collate relevant databases.

2 Plant/edaphic relations:

a Investigate physical soil properties of the analogue sites and tease out physical versus chemical constraints to plant presence and abundance. (Soil chemistry data, at least, are available.)

b Review information available from elsewhere in Australia on this topic.

c Re-survey original analogue sites if necessary, to acquire critical data, particularly on physical features of the soil profile (as these affect water availability).

d Consider plant surveys at mine-disturbed sites along the upper South Alligator River valley. The Scinto 6 site has slopes of rock-fragment overburden that have revegetated naturally. A comparison of this flora to that on adjacent undisturbed slopes may assist in assessing the effects of a fractured rock matrix on vegetation composition and density.

e Model vegetation patterns, conceptually and empirically, as a function of landform properties and soils in analogue sites. This is a step that both ***eriss*** and EWLS wish to take further. The modelling would be used to predict potential ecological outcomes for final landform designs.

f If required, survey additional 'hill' analogue sites: while the current data adequately characterises plant communities of different landforms, more replication may be required to develop statistically robust models of the type described in step e.

For step 2e, one of us (IH) proposes applying terrain analysis to the vegetation patterns determined from this study. The tenet of this investigation is that the geomorphic properties that distribute water and nutrients in the landscape exert control over the distribution of plant communities and ecosystem function. Understanding the way in which water and nutrients are distributed in hill slope environments, similar to the Ranger mine landform, could establish the pattern and form of interaction between biological communities and the landscape at a scale that is appropriate for planning mine rehabilitation at Ranger.

The outputs from the full study will provide a firm basis for:

1 selection of an appropriate distribution of species for initial planting on the constructed Ranger landform, and

2 providing an envelope of possible natural outcomes against which the progress of evolution of the plant assemblage on the Ranger mine landform can be quantitatively assessed with respect to ER 2.2a

Acknowledgments

Thanks to Peter Bayliss, David Jones and Paul Reddell who provided valuable comments on a draft of this paper or on analogue concepts raised in the paper.

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Key aspects of native flora seed biology that support Ranger mine rehabilitation goals

P Bayliss & S Bellairs[1]

Introduction

The aim of this project is to determine seed viability, dormancy, longevity and germination characteristics of native plant species local to the Ranger mine site in order to aid reliable germination and promote establishment of diverse local vegetation on rehabilitated landforms. Kakadu National Park contains a diverse range of native plant species, and ERA is required to rehabilitate the Ranger mine site with a selected range of these species. EWLS/ERA and SSD are collaborating with Charles Darwin University (CDU) and Kakadu Traditional Owners (principally Kakadu Native Plant Suppliers) to investigate the seed biology of local species with potential for use in revegetation. A broad range of species will be investigated so that information is available on which species can be effectively established from seed for later discussions between all stakeholders on choosing species for inclusion in the rehabilitation mix. An Australian Research Council (ARC) Linkage application was submitted in the April 2005 round to fund a PhD project and a post-doctoral position at CDU to research aspects of seed biology relevant to the succcessful revegetation of Ranger. Partners in the application were ERA and EWLS, Department of Business, Industry and Resources Development, Office of Supervising Scientist and Charles Darwin University. Despite an excellent application, substantial cash and in-kind contributions from Industry Partners, and highly favourable reviews at all stages, the bid failed. Although partners decided to re-submit to ARC in the November 2005 round, it was decided also to access the partner cash and in-kind commitments in order to commence work this dry season. Delays to critical research caused by seeking high risk funding options will have negative impacts on revegetation timelines. Hence, a full-time research position based with Dr Sean Bellairs at CDU will be advertised immediately.

Progress

This project is reported in two parts (following papers). The first was prepared by Honours student Kate Sangster and her supervisor Dr Sean Bellairs of Charles Darwin University, and reports on research progress into germination of a selection of native grass species. The second part was prepared by Dr Mark Gardener as a report to EWLS, and summarises progress in establishing a commercial seed collecting enterprise by Kakadu Tradional Owners Peter Christophersen and Sandra McGregor (Kakadu Native Plant Supplies, KNPS), funded by ERA Pty Ltd.

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1 Charles Darwin University, Darwin NT.

Key aspects of native flora seed biology that support Ranger mine rehabilitation goals

Part 1: Seed biology of selected Australian native grass species

K Sangster[1] & S Bellairs[1]

Background

Native grasses are an important part of the savanna landscape in the Top End of Australia. They have a range of crucial ecological roles and provide food and shelter to native fauna. Native grasses can also have an important role in rehabilitating land following mining activities. In general, grasses are used post mining to stabilise the soil, which aids in water retention, controlling erosion and creating a primary habitat for the establishment of other plants. Exotic grasses are often used for land rehabilitation as they are quick to establish from seeds, therefore providing fast vegetation cover. However exotic grasses can become problem weeds and may out compete native species if the rehabilitation aim is to establish a native species community.

Currently plans are underway for the rehabilitation of the Ranger mine site in Kakadu National Park. Native grasses are an important component of the savanna landscape in this region and therefore need to be replaced. It is also necessary to use only native species so that exotic species are not introduced into the National Park area. However, seed biology factors have limited the use of native grasses in other projects. Issues concerning seed viability and seed dormancy can result in low germination making the use of native grasses inefficient and impractical.

The aim of this project is to successfully germinate a selection of native grass species from the Ranger mine site region that have the potential to be of use in rehabilitation. Objectives to achieve this aim are to:

- identify species within the Ranger mine site area with the potential for use in rehabilitation;
- assess the seed viability of selected species; and
- determine which dormancy mechanisms are present and to trial dormancy breaking treatments to improve germination.

Methods

Seeds were hand-collected on the Ranger minesite then cleaned, sorted and dried. Seed viability was assessed using tetrozolium solution, which stains metabolically active tissue red, applied to the caryopsis and embryo. The degree of stain absorbed, and therefore the level of

[1] Charles Darwin University, Darwin NT.

viability, was visually assessed under a microscope. Germination trials were undertaken by placing the seeds on moist filter papers in Petri dishes. Petri dishes were incubated at 30°C for 30 days and germination monitored. Treatments were applied to seeds to determine the effect of husk removal, seed coat scarification, gibberellic acid, smoke water, potassium nitrate and darkness on germination and dormancy.

Progress to date

A meeting was held in Kakadu in February 2005 to determine which type of grass species would be most suited to rehabilitation at Ranger. Attendees at the meeting included Peter Bayliss (***eriss***), Sean Bellairs (CDU), Peter Christophersen (KNPS), Andrew Speechly (ERA) and Mark Gardner (EWLS). It was decided that the species selected should be perennial and produce light fuel loads to minimise fire risk. Seeds were collected from the Ranger mine site in late April over three days. Five species, *Heteropogon triticeus, Alloteropsis semialata, Eriachne schultziana* and two *Eragrostis* spp. were collected. These species are perennial, have light fuel loads and it was possible to collect a few thousand seeds of each species in a couple of hours. The seeds were then sorted and dried at CDU. Viability was assessed and the results recorded. Germination trials of each of the five species were then undertaken without any specific treatments to test for the presence of dormancy mechanisms. Following this the covering structures were removed from the caryopsis and germination was trialed to see if the covering structures were acting as a dormancy mechanism.

The results from the viability testing show a high level of viability, with at least a quarter of all species appearing to be clearly viable, and a significant proportion being potentially viable (table 1). In the germination trials with out any specific treatments (seeds with glumes, palea and lemma intact), there was no germination besides a small percentage of *Eragrostis* sp. 1 (figure 1). The removal of covering structures appeared to increase germination, particularly in *E. schultziana* and *H. tritceus*

Table 1 Viability of the grass seeds as assessed using tetrazolium – mean (± standard error)

Species	% viable	% possibly viable	% non viable
Alloteropsis semialata	33 (3)	33 (3)	33 (3)
Eragrostis sp. 1	36 (3)	43 (8)	20 (10)
Eragrostis sp. 2	36 (3)	36 (3)	26 (6)
Eriachne schultziana	26 (6)	23 (3)	50 (5)
Heteropogon triticeus	63 (6)	30 (5)	6 (3)

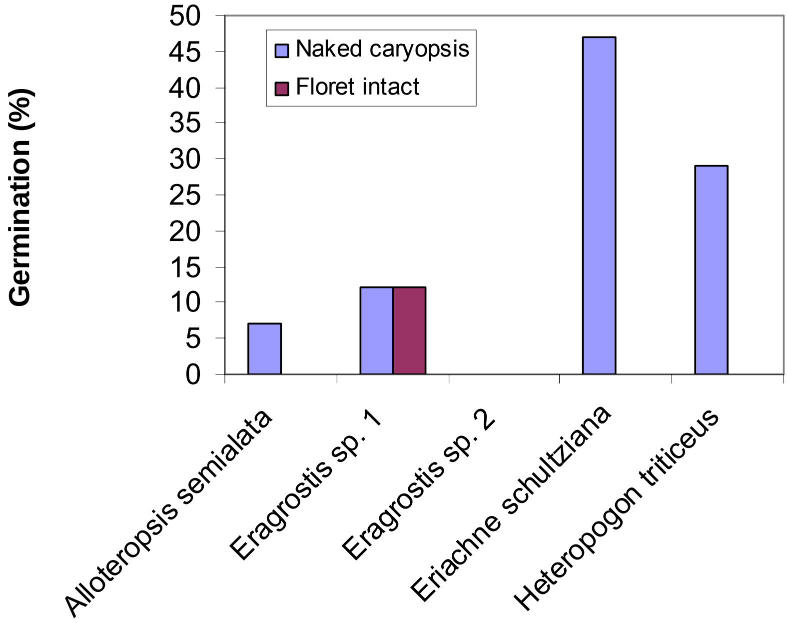

Figure 1 Total germination over 30 days of intact seeds and seed with covering structures removed

Preliminary conclusions

The reasonable ease of collection and the reasonably high level of viability in these species supports their potential use in rehabilitation programs. The very low level of germination in the trial with the untreated seeds (seeds intact) indicates that there is some form of dormancy mechanism(s) inhibiting germination in all five species. The increase of germination following the removal of the covering structures suggests that the covering structures are acting as either a mechanical or chemical barrier to germination. It is important to note that the initial viability of the seed lots will need to be considered along with the number of germinates per trial in order to properly determine the success of treatments.

Work to be completed

Work on the dormancy mechanisms present and effective treatments to overcome dormancy will continue to be investigated. The information from these investigations will form part of an Honours thesis completed in November 2005.

Key aspects of native flora seed biology that support Ranger mine rehabilitation goals

Part 2: Progress on Kakadu Native Plant Supplies Project[1]

M Gardener[2], P Christophersen[3] & S McGregor[3]

Summary

The Kakadu native plant project is progressing extremely well, is a model of successful Aboriginal enterprise and is based on collaborations between several industry and government partners. Kakadu Native Plant Supplies (KNPS) have collected, cleaned, catalogued and stored seeds from at least 25 plant species. KNPS have received significant training in aspects of nursery and business management. This training is on going and increases local capacity. By mid August 2005 the nursery will be fully functional and the first seed will be sown in late August. It is expected that KNPS will be able to produce the necessary seedlings by the end of the year to meet their contractual obligations with ERA.

Seed collection

To date Kakadu Native Plant Supplies have collected seed of at least 10 species listed in the contract (seven essential species, two highly desirable species, one other species of interest). These are local provenance seeds collected within a 50 km radius of Ranger mine. A further 15 species that are thought to be useful to revegetation at both Ranger and Jabiluka (Djarr Djarr) have been collected. Seeds have been cleaned and packed for storage. A log has been kept for collected seed and a database is currently being developed. Not all seeds on the contract list have been collected because the project has only been running since April 2005 and many species have yet to produce seeds.

Training

Kakadu Native Plant Supplies has undergone several days of training with Aboriginal Landcare Employment Program at Greening Australia including: plant identification, collection, maturity, cleaning, sorting (figure 1), storage and cataloguing of seeds (figs 1 & 2). They have also covered several units on Occupational, Health and Safety. Furthermore, they have undertaken specific training in grass identification and collection techniques. Training regarding plant propagation, nursery hygiene and maintenance is scheduled for early August 2005.

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[1] This report is based on a visit to Paradise Farm on 22 September 2005, several conversations with Peter Christophersen and with Greening Australia staff (Lesley Alford and Don Duggin).

[2] Earth Water Life Sciences, Darwin NT.

[3] Kakadu Native Plant Supplies, Jabiru NT.

Figure 1 Peter Christophersen at work sorting seeds from eucalypt fruits

Figure 2 A variety of fruits drying before processing

Business management and business support were also identified as key needs. Kakadu Native Plant Supplies has received a four-day training course in a Business Management Program and has adopted the Quick Books software to do all accounting. Kakadu Native Plant Supplies has also purchased a new computer system to support business management.

Nursery

Kakadu Native Plant Supplies has started preparing the ***eriss*** glasshouse facilities for plant propagation. By the middle of August 2005 an irrigation system will be installed, and a system of moveable shade will be erected. All potting medium and pots will be purchased shortly. The only barrier to plant propagation is the use of pesticides and fungicides which are not permitted because of possible interference to nearby ***eriss*** aqua-cultures. Problems with disease should be mostly overcome by good hygiene measures.

Plant propagation

Plant propagation is scheduled to start at the end of August. This is the latest date to sow some of the more difficult to grow species to produce seedlings by December 2005. Kakadu Native Plant Supplies have a contractual obligation to provide at least 3000 seedlings to ERA by 15 December 2005. It is expected that they will meet this target. It is likely that these 3000 seedlings will form part of the approximately 8000 seedlings required for revegetation of Djarr Djarr camp in Jan 2006. Many species required for the Djarr Djarr revegetation have yet to produce seeds and will not do so before the end of August when seeds are needed for planting to produce January 2006 seedlings. In this case, non-provenance seeds may need to be purchased (eg Top End Seeds). A decision is required by the end of August 2005 as to whether Kakadu Native Plant Supplies will be able to supply all required plants for the Djarr Djarr revegetation project.

Bioaccumulation in traditional Aboriginal bushfoods

B Ryan, A Bollhöfer & P Martin[1]

Introduction

The aim of this project is to assess the radiation exposure to humans via the ingestion pathway and contribute data that will aid in the development of dose assessment models for future users of rehabilitated uranium mine sites and for the general public.

Previous research on bioaccumulation of radionuclides in Aboriginal bushfoods has been carried out primarily for radiological impact assessment purposes in relation to current uranium mining activities in the region. Early studies conducted by ***eriss*** have focused on aquatic animal and plant species (Johnston et al 1984, Johnston 1987, Pettersson et al 1993, Martin et al 1995, Martin et al 1998). This has been due to the identified importance of the aquatic transport pathway during the operational phase of uranium mining operations. Martin et al (1998) have estimated the radiation dose received from the consumption of aquatic foodstuffs due to a simulated releases of RP2 water to Magela Creek, which is dominated by the intake of radium-226 in freshwater mussels due to the high concentration factors and their place in Aboriginal diet. The ingestion pathway has been identified as the major contributor to the mining related radiological dose to humans of the area.

With rehabilitation there will be radiological protection issues associated with the land use by local Aboriginal people and a shift towards terrestrial food sources that may grow on parts of the rehabilitated mines, Nabarlek and Ranger and also the abandoned South Alligator River Valley (SARV) mines. These foodstuffs include both aquatic and terrestrial animals and plants. Recently Ryan et al (2005) published radionuclide data associated with fruit and root vegetables in the ARR. It can be assumed that the highest doses to humans will be received from the consumption of foods from the vicinity of a contamination source. Therefore, the dose assessments need to be site specific, and the radiation dose model has to include local habits and human land use, and land use expectations, of the area.

Methods

In early 2005 SSD, in conjunction with Traditional Owners from the SARV, collected fruit and yam samples from the abandoned SARV mill site (figure 1). Traditional Owners for Nabarlek and SSD staff also spent time discussing traditional diets and collecting fruit samples for analyses at the rehabilitated Nabarlek mine.

As part of the dietary information that is needed to update dose assessments a questionnaire has been developed, under the guidance of the SSD Aboriginal Communications Officer, for distribution to local Aboriginal people. The information gathered from the discussions, analyses and questionnaire will help resolve issues relating to the rehabilitation of the Ranger mine site and update our dietary knowledge of the people living in the vicinity of the mine.

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[1] Formerly SSD; now Agency's Laboratories Seibersdorf, IAEA, A-1400, Vienna, Austria.

Figure 1 SSD employee at the abandoned SARV mine site with Traditional Owners and Parks Australia North Ranger digging for yams

Results

To aid in the identification of knowledge gaps associated with the assessment of the radiation health risk to humans via the biophysical pathway, SSD has begun collecting and reviewing all available information, both in hard and electronic form, from the Alligator Rivers Region. This information comprises more than two decades of radionuclide analyses and results including activity concentrations and concentration factors for key radionuclides in both aquatic and terrestrial animals and plants. Water and sediment data have also been included where relevant, and data quality has been checked when possible. Table 1 shows a summary of the available data. From this table it is apparent that more information is needed on radionuclide concentration and concentration factors for terrestrial flora and fauna, specifically adjacent to the Ranger mine.

The existing data are being collated and organised by location, species, radionuclide activity and concentration factor and are currently being incorporated into a Geographical Information System (GIS). This system offers descriptive attributes in tabular form and graphical information that are associated with spatial features (figure 2). The bushfood GIS will also be used for the presentation of results to stakeholders and to provide some assistance to SSD in the gap analysis of the data.

References

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Pettersson HBL, Hancock G, Johnston A & Murray AS 1993. Uptake of uranium and thorium series radionuclides by the waterlily, *Nymphaea violacea*. *Journal of Environmental Radioactivity* 19, 85–108.

Ryan B, Martin P & Iles M 2005. Uranium-series radionuclides in native fruits and vegetables of northern Australia. *Journal of Radioanalytical and Nuclear Chemistry* 264(2), 407–412.

Table 1 Summary of SSD bushfood collection sites and samples

Location	Animals				Plants	
	mussel collections	fish collections	other aquatic	terrestrial	aquatic	terrestrial
Barralil			1			
Bowerbird	1		2			
Buffalo BB	1					
Cannon Hill	2					
Cooper Ck	2					
Corndorl BB	1					
Catfish Ck		3				
Deaf Adder Gorge						
Djalkmarra					4	1
Drum Ck				1 (Buffalo)		
East All. Ranger St.						2
Flying Fox Ck	1					
Georgetown BB	8	6	3		1	
Goomadeer	2					
Gurnirdal		2	6			
Jabiluka						
Leichhardt BB	1					
Lightning Dreaming	1					
Long Harry BB	1					
Magela Xing		1				
Magela west				6 (wallaby/geese)		
Maningrida			1	3 (geese)		
Mudginberri BB	9	8	3		1	
Mamukala						1
Nabarlek						
Nourlangie						
Ranger Lease		2				3
Red Lily				2 (buffalo)		
Sth. A. Ranger St.						1
Sth. A. Valley	3	2				9
Sandy BB	3					
Terminator Ck				1 (pig)		

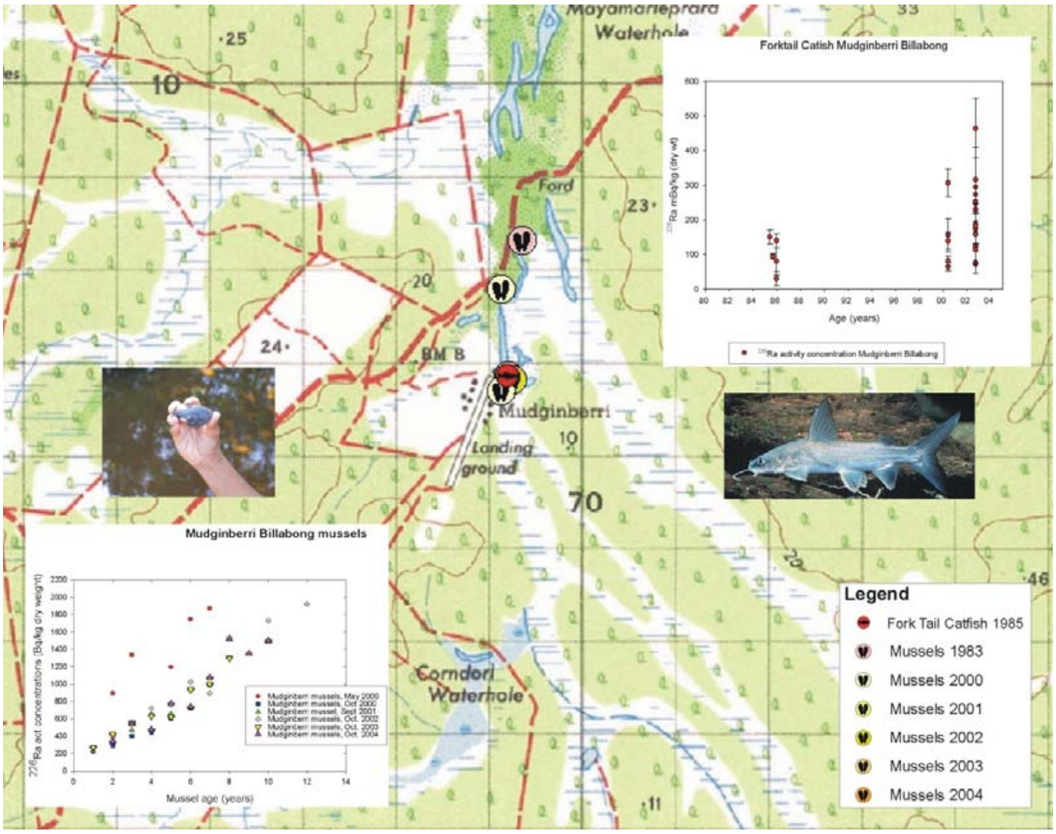

Figure 2 Screen shot of bushfood GIS showing Mudginberri Billabong sample details

Assess Quickbird data for weed mapping and monitoring at Ranger

K Pfitzner

Introduction

Weed mapping on the Ranger and Jabiluka leases currently involves intensive ground surveys that are conducted annually. Although ground surveys may provide accurate information on weed species present and their distribution and intensity of infestation in the areas surveyed, they are expensive in terms of human resources and restricted to areas accessible by road. Whilst helicopter surveys overcome problems of accessibility, they are expensive and entail observer errors associated with detection and identification.

High-resolution satellite imagery, such as DigitalGlobe ‘Quickbird’ data, launched in 2002, offers potential for the mapping of weeds. Vegetation assessment and weed identification at the Nabarlek minesite using Quickbird data and field sampling has shown promising results. The aim of this study was to investigate the utility of Quickbird satellite imagery for mapping and monitoring of weed distribution for input into the ERA Weed Management Strategy. In addition, the objective was to assess the suitability of such data for monitoring the success of the re-vegetation phase of the Ranger uranium mine.

EWLS acquired Quickbird multispectral and panchromatic images for the Ranger mine site in February 2003 and April 2004, and corresponding ground survey data in March 2003 and April 2004, respectively. These datasets from different times of year facilitate the investigation of the potential effect of seasonal variation on spectral signatures. Such extensive survey data provided the opportunity to test the suitability of remotely sensed data, providing ground-truthing points representing specific weed species and densities.

The objectives of this project were to: combine image data (transformations, vegetation indices and image statistics) in conjunction with field-based data (location and description); extract Quickbird spectra of weed and native vegetation endmembers and determine their separability; use a variety of classification parameters to map separable vegetation types; produce a contingency matrix from the field-data for accuracy assessment; and produce a location map of vegetation cover that may be exported to vector format for GIS compatibility. In addition to the above spectral analyses, predictive modelling was to be explored combining spectral data and other data collected during the field survey.

Progress to date

Preliminary findings of an investigation into the applicability of Quickbird satellite imagery for mapping dominant weeds at the Ranger minesite are reported (Pfitzner et al 2004, Welch et al 2004). In summary, a thorough analysis was not possible due to unplanned limitations of the ground-based data and the satellite product supplied. The ground data were inappropriate for correlation with the remotely sensed data. The ground data were characterised by wide abundance class ranges and heterogenous covers. For example, high, dense infestations of weeds were characterised in the field data, with a range from 26–100% cover. Field sampled data also included canopy cover as well as ground cover. Field data of 100% homogenous cover are required for remote sensing feasibility studies of cover separability. In addition, the satellite product obtained was map-orientated (only) and not pan-sharpened. The implications were that: pure stands of weeds could not be discriminated from the ground data supplied; ground data were often comprised of areas smaller (such as linear occurrences along roads) than the Quickbird multispectral resolution (~2.5m); the geometric inaccuracy of the image data supplied meant that accurate association between image data and ground features could not be established; and without pan-sharpened data (~60 cm pixel size) analysis was limited to the 2.5 m pixel.

In order to undertake a robust test of the suitability of Quickbird data for weed mapping at Ranger, Pfitzner et al (2004) recommend that remotely sensed data be obtained that are orthorectifed and spatially sharpened, and that field-based data on weed coverage be specifically designed for the purpose of the remote sensing analysis.

Strategic research commitment is needed to develop remote sensing methods for mapping weeds and to monitor revegetation progress. Experience from Nabarlek suggests that a future survey design, which combines ground-based and remote sensing methods, would overcome the limitations of both and still be cost-effective. An assessment of the data ***eriss*** obtained from the DeBeers Hyperspectral Mapper in 2004 should follow any thorough assessment of Quickbird multispectral data in order to compare spectral separabilities of both remotely sensed data types for discriminating and mapping weeds.

References

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Quantify stream sediment transport characteristics for Gulungul Creek to assess the impact of mine site erosion and rehabilitation performance of Ranger mine

DR Moliere, MJ Saynor & KG Evans

Introduction

The catchment area upstream of Gulungul Creek, a small left bank tributary of Magela Creek, contains part of the Ranger mine tailings dam. Once rehabilitation of the Ranger mine commences, earthworks associated with construction of the the rehabilitated landform, including removal of the tailings dam and subsequent erosion, may elevate sediment movement in Gulungul Creek. It is important that the hydrology and sediment transport characteristics in the Gulungul Creek catchment are investigated to establish baseline before rehabilitation at the mine site occurs.

The aims of this project are (1) to monitor and determine baseline stream fine suspended-sediment and bed sediment movement characteristics in the Gulungul Creek system to assess minesite impact and rehabilitation success; and (2) to monitor and determine the hydrology characteristics of the Gulungul Creek system as the underlying driver behind impact assessment.

To establish an on-going data collection system, this project has four tasks:

1 Install a gauging station network in Gulungul Creek upstream and downstream of the Ranger mine,

2 Implement a cross-section monitoring network in Gulungul Creek,

3 Calibrate *in situ* turbidimeters in Gulungul Creek to measure fine suspended-sediment concentration on a continuous basis, and

4 Derive long-term hydrological characteristics for the Gulungul Creek catchment, including a flood risk assessment.

Progress

Task 1

A gauging station was installed upstream of Ranger mine (Gulungul Creek upstream – GCUS) (fig 1) in November 2003. The station G8210012 (fig 1), which was operated by DIPE between 1971 and 1993, was also re-instrumented by ***eriss*** in November 2003. A third gauging station was installed downstream of Ranger mine (Gulungul Creek downstream – GCDS) (fig 1) in November 2004. Rainfall and streamflow are collected at all three stations on an almost continuous basis. Stream suspended sediment is monitored both upstream and downstream of the mine (GCUS and GCDS) using turbidimeters installed at the two stations. Automatic pump samplers were installed prior to the 2004–05 wet season at the two stations to collect water samples for a range of flow conditions in order to calibrate the turbidimeters to measure mud concentration.

Task 2

A cross-section monitoring network (fig 1) was established in the dry season of 2002 to assess channel stability and change in particle size distribution of bed sediments. The cross sections are surveyed and bulk bed material samples are collected annually. At some cross sections, scour chains have been installed in the bed to measure amounts of scour and fill during each wet season. The data from 2002 are contained in Crossing (2002) and the data from 2003 and 2004 are contained in Saynor et al (2005). Data interpretation with respect to establishing baseline conditions will commence after several more years of sampling.

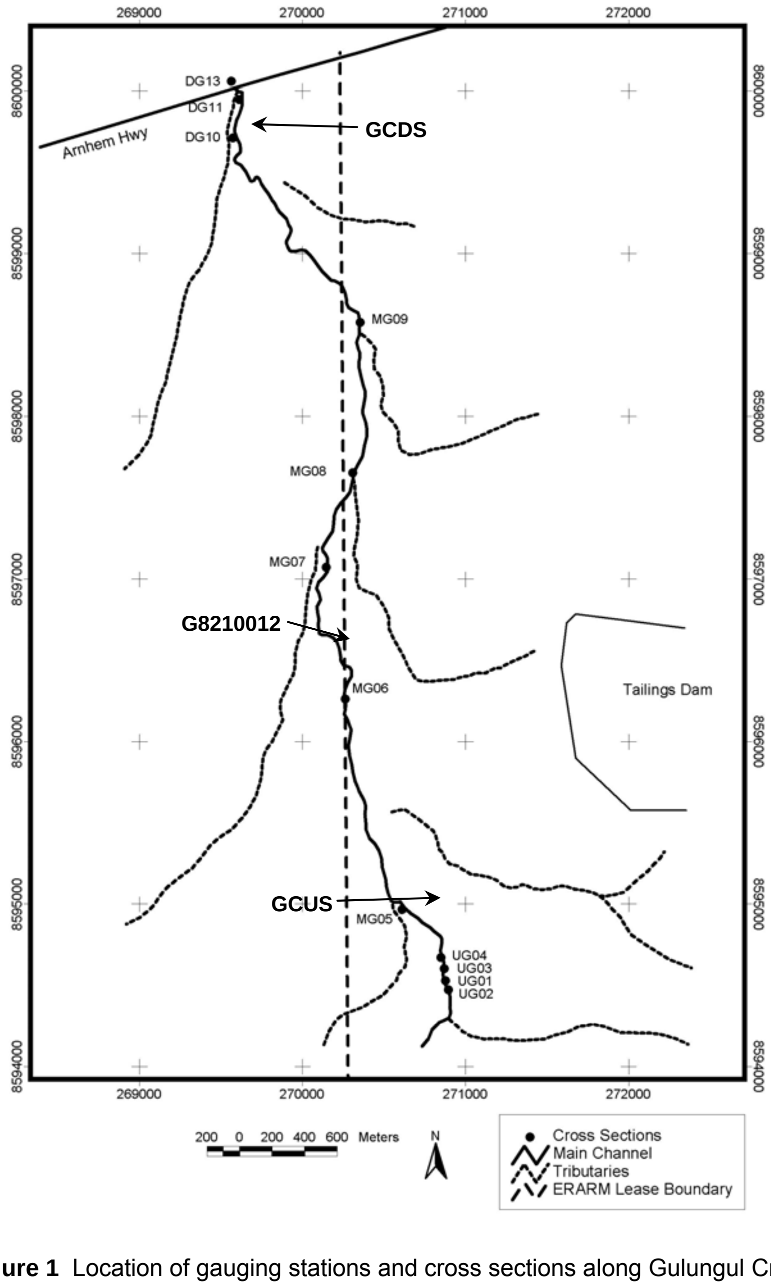

Figure 1 Location of gauging stations and cross sections along Gulungul Creek

Task 3

As mentioned in Task 1 above, water samples collected by the stage-activated pump sampler will be used to calibrate the turbidimeters to measure mud concentration. It is planned that mud concentration data will be monitored using *in situ* turbidimeters over the next few years to develop an understanding of the fine sediment movement characteristics within the catchment before rehabilitation at the mine site occurs. A significant relationship between turbidity and mud concentration has been fitted for the station upstream of Ranger (GCUS) using data collected during the 2004–05 wet season (fig 2). However, instrumentation problems at GCDS during 2004–05 meant that flow data collected prior to mid-March were considered unreliable. As a result, an insufficient number of water samples were collected during the year to fit a turbidity-mud concentration relationship for GCDS.

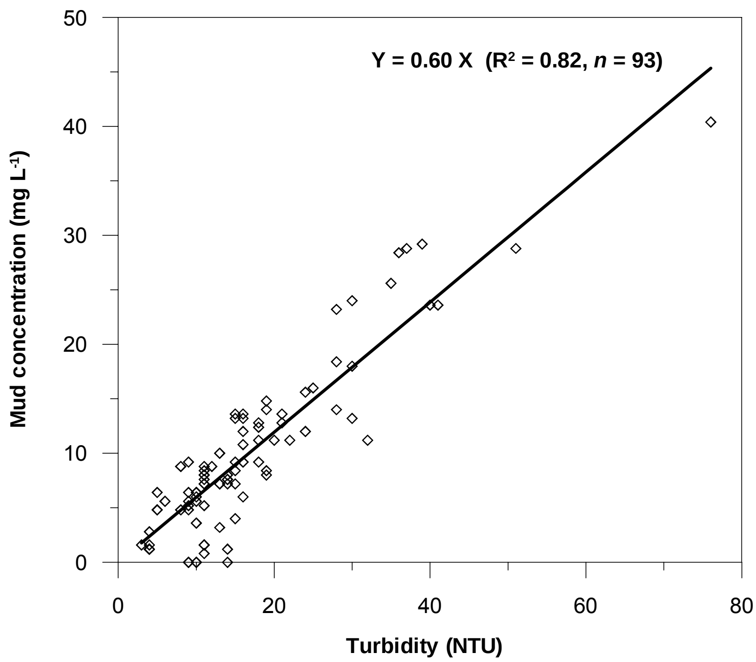

Figure 2 Fitted relationship between turbidity and mud concentration at GCUS using 2004–05 data

Task 4

Long-term runoff characteristics have been derived for Gulungul Creek based on flow data collected at G8210012 (fig 1) between 1971 and 1993 (Moliere 2005). However, because this station is neither entirely upstream nor downstream of the Ranger mine site influence, it is also important to determine the runoff characteristics at GCUS and GCDS, particularly before rehabilitation at the mine site commences. It is unlikely that these two stations (GCUS and GCDS) will have a significant runoff record for risk analysis by the time rehabilitation at Ranger mine is initiated. Therefore, it is important to investigate whether or not the long-term runoff record at station G8210012 can be used to extrapolate the record at the new station locations. If a significant regression relationship between observed peak discharges at the two new stations with corresponding peak discharges at G8210012 can be established using the next few years of runoff data, the relationship could be used to estimate values at the two new stations for the period of record available at G8210012 (1971–1993). Flood frequency curves could then be established for GCUS and GCDS using the extended runoff record.

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Feasibility study of implementation of sediment monitoring system in Corridor and Magela creeks upstream and downstream of Ranger mine

DR Moliere & MJ Saynor

Introduction

Once rehabilitation of the Ranger mine commences, earthworks associated with construction of the rehabilitated landform and subsequent erosion may elevate sediment movement in nearby Corridor Creek and also Magela Creek.

The aim of this project is to determine whether it is practical to set up sediment monitoring systems along Corridor Creek and Magela Creek. Such a system is currently in place within the Gulungul Creek and Ngarradj catchment areas. Gauging stations have been installed along these creeks to monitor flow and sediment concentration upstream and downstream of the mine sites. Flow at these stations is generally less than 2 m deep and is contained within a single channel. Flow within Corridor Creek is similar to Gulungul Creek and Ngarradj in terms of water depth but has a series of weirs installed along the channel that could influence sediment movement. Magela Creek has multiple channels and significantly higher flows than Gulungul Creek and Ngarradj which could make sediment monitoring difficult along this creek.

Progress

Preliminary observations have been made along Magela Creek during wet season flows to try and map the channels that have active flow in them, although no firm decision on the location of the sediment monitoring system in Magela Creek has been made. As part of a continuous monitoring program, SSD will be installing three continuous monitoring stations in Magela Creek prior to the 2005–06 wet season. One of these will be located along Magela Creek upstream of Ranger (MCUS) and the other two will be located downstream of Ranger near gauging station G8210009 in the central and western channel. These stations will be equipped to collect basic water parameters, including turbidity (which can be used to monitor suspended sediment movement). The data obtained by these stations will be assessed after the wet season to determine whether it is necessary to install automatic water samplers at each station to collect suspended sediment concentration data.

No progress has been made on whether or not a similar gauging station network should be established within the Corridor Creek catchment.

Part 3: Jabiluka

Contents[1]

3.1 Monitoring

KKN 3.1.1 Monitoring during the care and maintenance phase

[1] List of papers grouped by Key Knowledge Need.

Monitoring during the care and maintenance phase at Jabiluka

M Iles

Introduction

The Jabiluka project has now entered a long-term care and maintenance phase. While it was ARRTC's view that ongoing monitoring would be required throughout this period, SSD has wound back all ongoing monitoring such that this is now limited to water chemistry. The biological baseline/monitoring sampling program completed water sampling at the end of the 2003–04 wet season. Fish community results for that wet season were reported in the Supervising Scientist's annual report for 2003–04. Macroinvertebrate samples gathered during the 2003–04 wet season are still to be processed.

Chemical and physical monitoring of Ngarradj (Swift Creek)

Toward the end of 2003, Jabiluka entered a long-term care and maintenance phase. The site poses a very low risk to the environment. Consequently, the Supervising Scientist's water chemistry monitoring program at Ngarradj was reduced to monthly sampling for the 2004–05 wet season, augmented by automatic recordings of turbidity and hydrological data at six-minute intervals. The NT DPIFM resumed the role of performing check monitoring at Ngarradj, also on a monthly basis. These independent programs complement each other, providing approximately fortnightly water sampling and a combined dataset to assess the water quality at Ngarradj. ERA continued to carry out independent monitoring on a weekly basis.

The first water chemistry samples for the Supervising Scientist's 2004–05 wet season surface water monitoring program were collected from the Ngarradj downstream statutory compliance point on 6 January 2005. ERA commenced monitoring at that site on 29 December 2004, the day flow was first observed, and DPIFM commenced monitoring in the second week of January. The last samples were collected from Ngarradj on 10 May 2005, by ERA, shortly before flow ceased.

ERA, SSD and DPIFM data generally agree (table 1) with values and trends similar to those seen in previous years measured again this season. The water quality was very good throughout the season with only one exceedance of the electrical conductivity (EC) and the magnesium guideline (table 1) occurring.

- In early January (SSD data) EC at the downstream site was just above the guideline value. The corresponding EC at the upstream site was of a similar value, indicating that the elevation was part of a natural fluctuation in the system.
- The magnesium concentration exceeded the upper guideline in May (ERA data) just before flow ceased. When the water level in the creek drops toward the end of the season increases in magnesium concentrations occur, particularly at the downstream site, which naturally has higher concentrations than upstream. Therefore, the upper level for magnesium has always been a guideline and not a limit. This trend has been noted in

previous years in Ngarradj and at other creeks in the region (eg Magela and Gulungul Creeks).

All other key indicators remained within limits/guidelines. Uranium remained less than 0.5% of the limit throughout the season (figure 2), similar to previous years (figure 1).

The water quality objectives set to protect the aquatic ecosystems downstream of Jabiluka were achieved providing assurance that the environment remained protected throughout the season.

Table 1 Ngarradj (Swift Creek) 2004–05 wet season water quality upstream and downstream of Jabiluka

Parameter	Guide-line or Limit**	Organisation	Median		Range	
			Upstream	Downstream	Upstream	Downstream
pH	3.9–6.0	SSD/DPIFM	4.9	5.3	4.4 – 5.0	4.3 – 5.8
(field data)		ERA	5.0	5.3	4.7 – 5.8	4.8 – 5.7
EC (µS/cm)	21	SSD/DPIFM	15	16	13 – 24	12 – 24
(field data)		ERA	12	10	9 – 17	8 – 15
Turbidity* (NTU)	–	SSD/DPIFM	0.5	0.8	0.3 – 2.2	0.6– 2.0
		ERA	1.	2.	<1 – 6.	<1 – 7.
NO_3 (as NO_3) (mg/L)	1.26	SSD/DPIFM	<0.02	0.04	n = 1 only	<0.02 – 0.13
		ERA	0.02	0.02	<0.02 – 0.38	<0.02 – 0.31
Sulfate‡ (mg/L)	1.5	SSD/DPIFM	0.4	0.3	0.2 – 1.1	0.1 – 1.4
		ERA	0.3	0.3	0.2 – 1.2	< 0.1 – 1.0
Magnesium‡ (mg/L)	0.76	SSD/DPIFM	0.3	0.4	0.2 – 0.6	0.3 – 0.5
		ERA	0.3	0.4	0.2 – 0.4	0.3 – 0.8
Uranium‡ (µg/L)	6.	SSD/DPIFM	0.007	0.010	0.005 – 0.025	0.006 – 0.019
		ERA	0.011	0.012	<0.005 – 0.029	<0.005 – 0.029

ERA data taken from the ERA Weekly Water Quality Report 5 July 2005; * SSD data laboratory data; pH & EC based on field data – the common measurement to all organisations ‡ dissolved (<0.45 µm); **A compliance limit applies to uranium, management guidelines apply all other parameters shown; ERA data *n* = 20, SSD & DPIFM data *n* = 1 – 8.

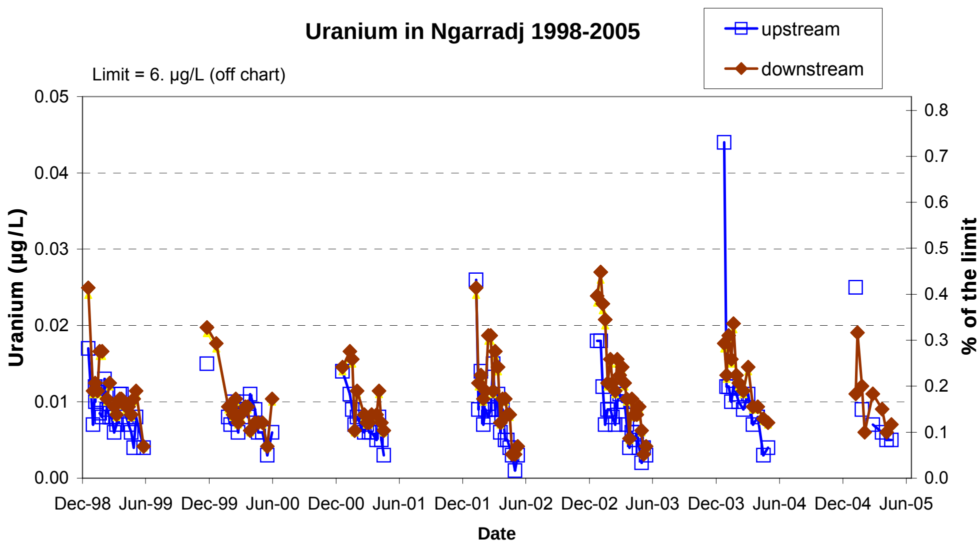

Figure 1 Uranium concentrations in Ngarradj since the 1998–99 wet season (SSD data 1998–99 to 2003–04, SSD & DPIFM data 2004–05)

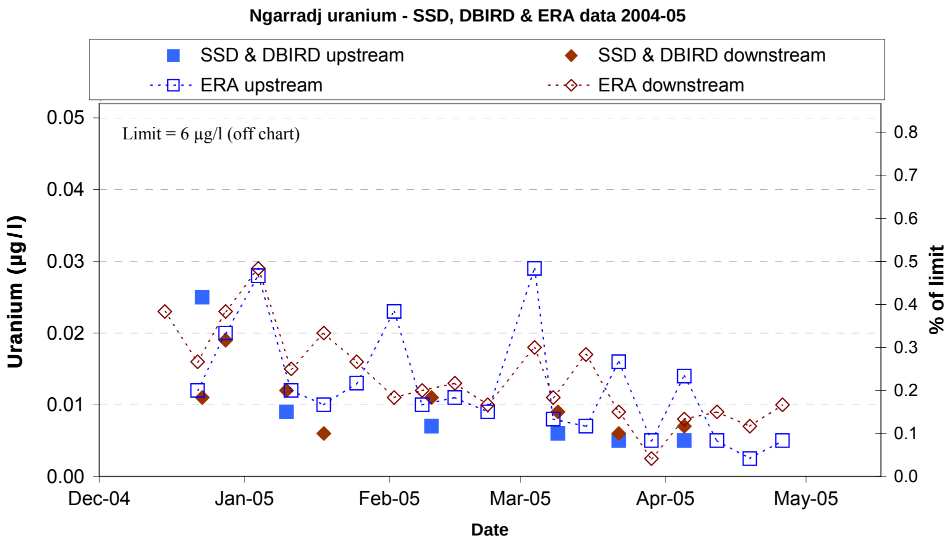

Figure 2 Uranium concentrations measured in Ngarradj by SSD, DPIFM and ERA during the 2004–05 wet season

Monitoring suspended sediment at Jabiluka 1998–2003: establishing baseline

KG Evans, DR Moliere, MJ Saynor, WD Erskine[1] & MG Bellio[2]

Introduction

A stream monitoring program was implemented in the Ngarradj catchment in the late dry season of 1998 and prior to the 1998–1999 wet season principally to assess geomorphic change in streams in the project site catchment and to obtain data to derive erosion model parameters (Erskine et al 2001). Rainfall, stream fine suspended sediment concentration [FSS][3], suspended bedload, solutes, EC, turbidity and stream discharge data were collected for four wet seasons (1998–2002). The data have also allowed (1) determination of baseline characteristics for the measured parameters in the catchment and (2) assessment of impact on water quality resulting from construction of the Jabiluka project site.

Methods

Three river gauging stations were installed in Ngarradj (fig 1 in Saynor et al 2006) prior to the 1998–1999 wet season (Erskine et al 2001): (1) on the unimpacted main channel upstream of the Jabiluka project site UM); (2) on the unimpacted East Tributary channel upstream of the confluence with the main channel (ET); and (3) on the main channel downstream of the project site and the major and minor tributaries (SC) and collected JML data. Changes in the western part of the catchment where the project is located should be seen downstream at SC, through comparison with the upstream ET and UM data.

The Australian and New Zealand water quality guidelines (WQG) (ANZECC & ARMCANZ 2000) were used to determine numerical parameter values for SC which when exceeded will trigger a management response. Two methods were used: (1) comparison of the downstream SC site with percentile limits at the upstream UM site, and (2) a before-after-control-impact, paired difference design (BACIP) where the upstream site UM is before impact in a spatial sense and the downstream site SC is after impact in a spatial sense (Evans et al 2004). In both cases the ET site can be used to confirm whether an observed elevated measurement at SC not observed at UM is (1) from the project-site catchment or (2) from ET and therefore a natural occurrence (eg fig 1). If elevated values are not observed at ET it is assumed that the source is from the project-site catchment.

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1 Formerly SSD; now Centre for Sustainable Use of Coasts & Catchments, School of Environmental & Life Sciences, University of Newcastle, Ourimbah Campus, PO Box 127, Ourimbah NSW 2258.

2 Formerly SSD; now International Water Management Institute (IWMI), PO Box 2075, Colombo, Sri Lanka

3 [FSS] is fine suspended-sediment concentration and comprises the mud [(silt + clay) < 63 μm > 0.45 μm] component of stream sediment.

Results

Upstream limits

Where data are not normally distributed, the WQG recommend a trigger value of the 80th percentile of parameter values of a suitable reference site. In this case the reference site of the downstream site, SC, is the upstream site, UM. Therefore, values measured at SC should be lower than the 80th percentile at UM. Proposed trigger values are, 80th, 95th and 99.7th percentiles representing different levels of interventions by supervising authorities and the stakeholders. The levels of intervention are still under discussion.

The trigger values for SC have been determined using the complete dataset from four years of monitoring (table 1). In the example given (fig 1), a number of SC data points are above the trigger levels. This is due to event related variability.

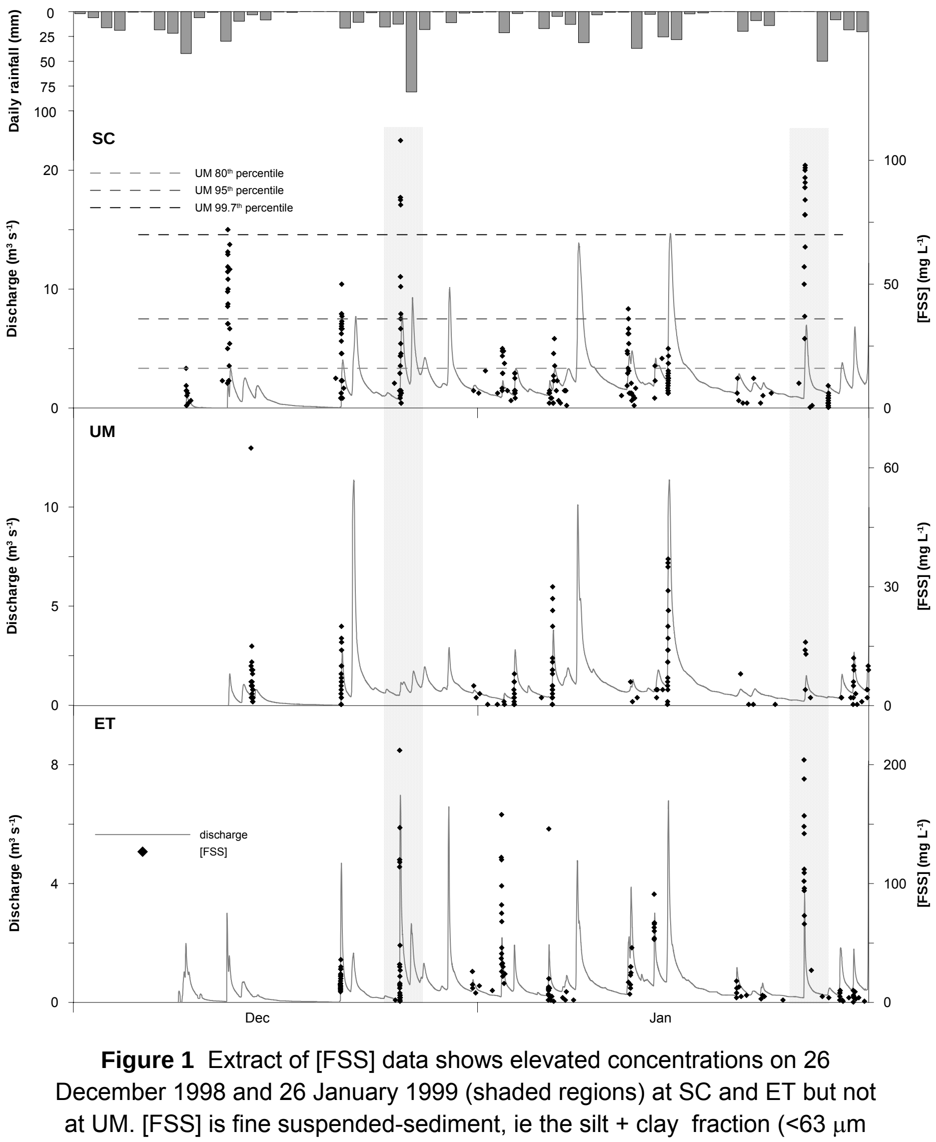

Figure 1 Extract of [FSS] data shows elevated concentrations on 26 December 1998 and 26 January 1999 (shaded regions) at SC and ET but not at UM. [FSS] is fine suspended-sediment, ie the silt + clay fraction (<63 μm >0.45 μm diameter).

Table 1 Trigger values for the downstream SC site derived using the upstream UM reference site

Percentile	Suspended bedload (mg L-1)	Suspended mud (mg L-1)	Solutes (mg L-1)	EC (µS cm-1)	Turbidity (NTU)
80	78	16	28	14.1	12
95	151	36	41	17.4	24
99.7	325	70	71	24.3	49

BACIP

UM and SC are treated as paired sites. The time period chosen for comparison was one calendar month. The parameter used to assess impact was the monthly median ($\tilde{\mu}$) parameter value at UM and SC because distributions were generally skewed. The test parameter used was the difference between the median concentration at SC and UM ($\theta_{SC} - \theta_{UM}$). Power analysis indicates that for the number of samples available in this study for an effect size of one standard deviation from the mean, the probability of a Type II (β) error with alpha of 0.05 is 0.20 with a power of 80%.

Since the distribution of the population of $\theta_{SC} - \theta_{UM}$ is normal, trigger values were set as +1σ, +2σ and +3σ respectively. Figure 2 shows $\tilde{\mu}$ for UM and SC and $\theta_{SC} - \theta_{UM}$ for [FSS] and trigger values. Outliers usually result from first flush, fire-impacted events at the start of the 1998–1999 wet season and the 2001–2002 wet season. $\theta_{SC} - \theta_{UM}$ occasionally exceeds +1σ but rarely exceeds +2σ. Values exceeding +2σ are infrequent and irregular and probably result from rainfall and hydrograph variation as expected in this variable natural system.

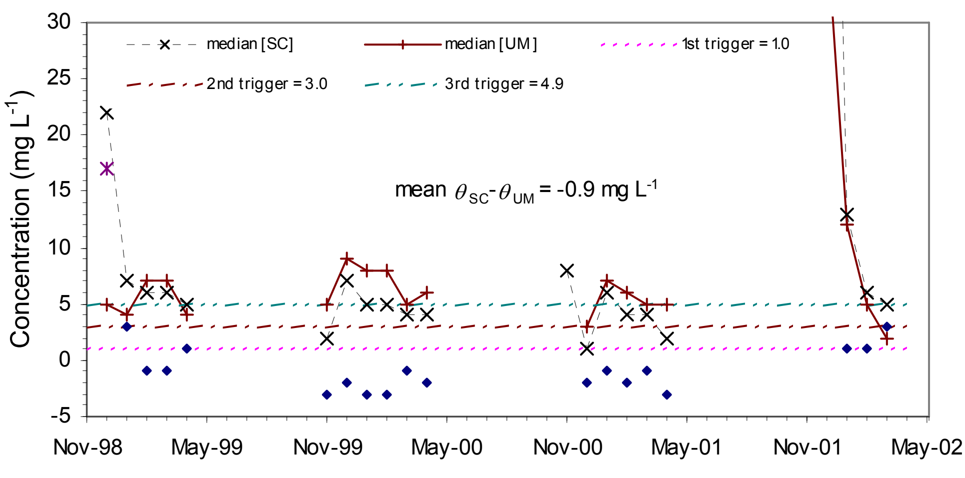

Figure 2 Temporal variation of $\theta_{SC} - \theta_{UM}$ for [FSS] and 1st, 2nd and 3rd order trigger values. Monthly median values for UM and SC are also shown.

Conclusions

The four years of monitoring have provided a high-resolution data set that is almost continuous. The system has high natural variability dependent on rainfall event and subsequent discharge and pre-wet season fire distribution and intensity. In general, parameter values are elevated at the commencement of the wet season until about February. This is caused by first-flush and early wet season removal of surface material detached during the dry season by agents such as bioturbation (including anthropogenic activity), wind erosion and surface desiccation. The analyses showed no observable impact from project construction in 1998 or during the study period. The impacts of dry season fires could be clearly seen. The data set provides good baseline information for future assessment at Jabiluka and demonstrates the need to view measured parameter values on a catchment-wide basis with knowledge of rainfall, discharge and fire distribution. Monitoring data collected during 2002–03 showed no measurable impact on the catchment as a result of the mine (Moliere et al 2003).

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Monitoring suspended sediment at Jabiluka: 2003–2005

DR Moliere, MJ Saynor & KG Evans

Introduction

The Jabiluka uranium deposit is located in the catchment of Ngarradj in the wet-dry tropics of the Northern Territory, Australia (see fig 1 in 'Baseline stream channel stability characteristics in the Ngarradj catchment' in Saynor et al 2006). The Ngarradj catchment will be the first to be affected should any impact occur as a result of mining operations at Jabiluka. In 1998 a stream gauging network was established to determine the pre-mining hydrological and suspended sediment transport characteristics of the Ngarradj catchment. Stream gauging stations were installed upstream (Upper Main – UM; East Tributary – ET) and downstream (Swift Creek – SC) (fig 1) of Jabiluka (Erskine et al 2001).

Since the 2003–04 wet season, data collection has been scaled down within the Ngarradj catchment and only rainfall, discharge and fine suspended-sediment concentration [FSS] data are being collected. During five years of monitoring at Ngarradj between 1998 and 2003, stream suspended-sediment concentration was determined by collecting water samples during the annual hydrograph and filtering and drying the samples in the laboratory (Erskine et al 2001, Evans et al 2004). The collection of water samples and the subsequent laboratory process was very labour intensive and expensive, particularly for monitoring fine suspended-sediment movement over the long term (ie an entire wet season). An investigation was conducted to implement continuous monitoring of turbidity in streams as an indirect measure of suspended sediment concentration.

Progress to date

Detailed turbidity data were collected at the three gauging stations within the Ngarradj catchment (SC, UM and ET) during the 2003–04 wet season using turbidimeters installed at each station. In order to calibrate the turbidimeters to measure [FSS], water samples were collected by the automatic pump samplers for a range of flow conditions and analysed for [FSS]. Significant relationships were fitted between turbidity and [FSS] data for each station (the fitted relationship for SC is shown in figure 1), which showed that the use of turbidimeters is a robust and efficient technique to monitor mud movement within the Ngarradj catchment (Moliere et al 2005a). However, water samples will continue to be collected over several wet seasons to validate or refine the turbidity-[FSS] relationship.

As discussed above, Evans et al (2004) derived numerical trigger values for impact assessment using [FSS] data determined by collecting water samples throughout the event hydrograph and filtering and drying the samples in the laboratory. The parameter used to assess impact within BACIP was the monthly median [FSS] value at each site and it is considered that these trigger values cannot be simply applied to the continuous [FSS] data collected by the turbidimeter. This is because the [FSS] data used to derive the trigger values were collected almost entirely during runoff events and only very few data were collected during baseflow conditions.

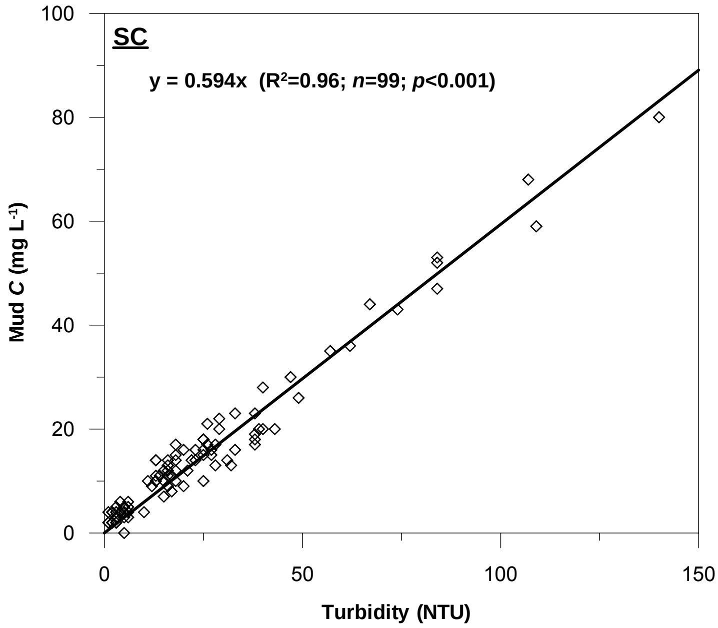

Figure 1 Fitted relationship between turbidity and mud concentration at SC using 2003–04 data

The continuous turbidity data were collected throughout the entire annual hydrograph (ie during both runoff events and baseflow conditions). Therefore, the monthly median [FSS] values for the two datasets cannot be compared. As a result, a variation of the BACIP analysis previously done by Evans et al (2004) was derived by Moliere et al (2005b) for impact assessment using event mud (fine suspended-sediment) loads derived from [FSS] data collected by the turbidimeter. This assessment uses an event-based BACIP design where SC and the combination of UM and ET are treated as paired sites and the comparison of ratios is used to assess impact. Therefore, only events where event loads were determined for all three stations were used in the analysis.

Figure 2 shows that the mean ratio of UM + ET mud load to SC mud load for the two-year monitoring period (2003–04 and 2004–05) is approximately one. The events of 'interest' are those that lie greater than one standard deviation below the mean ratio (ie <-1 SD) because these are events where elevated mud loads are measured downstream of Jabiluka at SC relative to the upstream combined load at UM and ET. For example, during 2004–05 there were two events below the -1 SD line (fig 2) and these were associated with the high magnitude events on 2–4 February discussed in Moliere et al (2005b). Nevertheless, the event-based BACIP analysis indicates that the ratios of event mud load observed at UM and ET to SC during these two events are not considered as outliers as they are within the 95% prediction intervals (ie within two standard deviations) of the mean ratio.

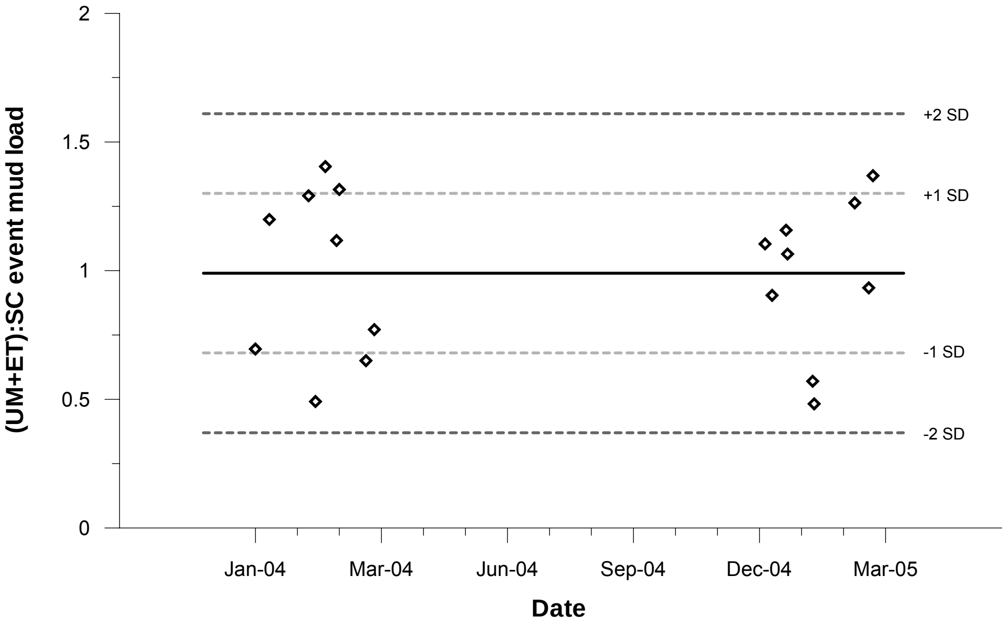

Figure 2 Temporal variation of the ratio of event mud loads measured at UM and ET to that at SC during 2003–04 and 2004–05 (indicated as ◇). The mean ratio and associated standard deviations are also shown.

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Baseline stream channel stability characteristics in the Ngarradj catchment

MJ Saynor, WD Erskine[1], DR Moliere & KG Evans

Introduction

In 1998, ***eriss*** installed three river gauging stations, two upstream (Upper Main – UM; East Tributary – ET) and one downstream (Swift Creek – SC) (figure 1) of the Jabiluka project area to monitor hydrology and suspended sediment transport within the Ngarradj catchment. At each station, rainfall, streamflow and suspended sediment concentration data were collected throughout the wet season. In addition, numerous cross sections, scour chains and erosion pins were installed along the main channel and several tributaries within the Ngarradj catchment to determine the channel stability and geomorphological characteristics of the catchment and any changes that may occur as a result of project area disturbance (Erskine et al 2001, Saynor et al 2004a).

Results

Rainfall is highly seasonal in the Ngarradj catchment with monthly totals greater than 150 mm being recorded at the peak of the wet season between December and March (Moliere et al 2002, 2003). Much lower totals are recorded during both the build up to (September to November), and the recession from (April and May), the wet season. Cross section and scour chain measurements were conducted between late 1998 and 2003 when rainfall was at or above average. Moliere et al (2002, 2003) estimated that the average recurrence intervals for annual rainfall for the 1998/1999, 1999/2000, 2000/2001, 2001/2002 and 2002/2003 water years (September to August, inclusive) were 13, 71, 21, 2 and 9 years respectively.

The seasonal streams gauged by ***eriss*** commenced flowing on 8 November (1999) at the earliest (streamflow did not persist after this first flush and recommenced on 20 November 1999) but usually on or after 20 November each year. The amount of rainfall before streamflow commenced varied between 225 and 440 mm. Streamflow generally persisted until between May and July each year, depending on the amount of wet season rainfall. The largest peak instantaneous discharges were recorded during the 1998/1999 wet season but the variation between years was minor, as was the variation in maximum flow velocity between years (Saynor et al 2004a).

A total of 56 permanently monumented channel cross sections were surveyed during each dry season between 1998 and 2004. In most surveyed river reaches the channels are reasonably stable apart from active nickpoint retreat on Tributary North and channel erosion by lateral migration, bed degradation and channel widening on Tributary Central (Saynor et al 2004a, 2006a). Aerial photograph interpretation showed that these geomorphic processes were occurring before the construction of the Jabiluka project and their rates of activity have not accelerated since the project site was developed.

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[1] Formerly SSD; now Centre for Sustainable Use of Coasts & Catchments, School of Environmental and Life Sciences, University of Newcastle, Ourimbah Campus, PO Box 127, Ourimbah NSW 2258.

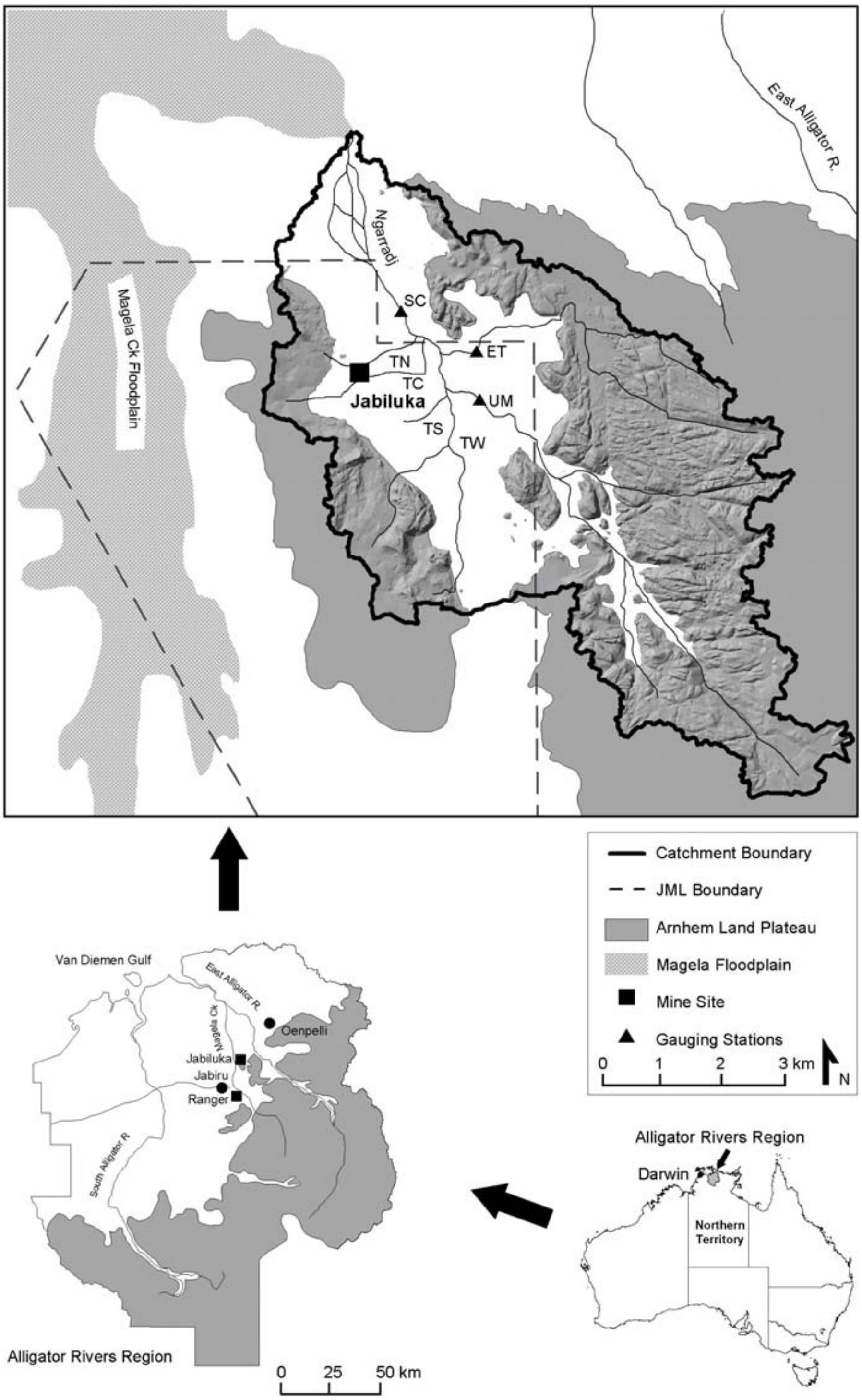

Figure 1 The Ngarradj catchment showing the Jabiluka Mineral Lease (project area), ***eriss***'s gauging stations and local creek names. SC refers to Swift Creek gauging station, TN Tributary North, ET East Tributary gauging station, TC Tributary Central, TS Tributary South, TW Tributary West and UM upper Swift Creek gauging station.

A total of 30 scour chains were installed on some of the surveyed cross sections to measure scour and fill during wet season floods. Scour and fill are active geomorphic processes in the Ngarradj catchment that result in the reworking of the sandy bed sediment. Mean scour and fill rates were determined for each reach for each wet season. Allowing for plus or minus twice the standard error of estimate of the mean, average scour and fill for the scour chains during each wet season in each measurement reach usually overlapped with each other (Saynor et al 2004a, 2006b). This indicates that mean annual scour and fill are not significantly different between reaches.

Bed material samples were also collected at each of the 56 cross sections during each dry season between 1998 and 2004. Particle size analysis was completed on all of these samples and graphic grain statistics were calculated. Statistical analyses of the grain size statistics showed that any annual changes at the sites downstream of the project area also occurred synchronously at the sites upstream of the project area (Saynor et al 2006c). The grain size statistics data constitute thorough baseline information for the Ngarradj catchment and can now be used to determine any subsequent changes due to future activities in the project site.

Up to four years of erosion pin measurements in the Ngarradj catchment have established that substantial bank erosion (up to 285 t/a) has occurred during the wet season on the project area tributaries by rapid lateral migration (Tributary Central) and by erosion of gully sidewalls due to a combination of within-gully flows and overland flow plunging over the sidewalls (Tributary North) (Saynor et al 2003, 2004b, Saynor & Erskine 2006). Bank erosion also occurred during the dry season by faunal activity, by desiccation and loss of cohesion of the sandy sediments, and by dry flow processes but at very low rates. Channels with dense riparian vegetation did not generate significant amounts of sediment by bank erosion. Deposition was also locally significant, despite the sandy bank sediments. Bank profile form and channel planform exert a strong control on erosion rates during the wet but not during the dry season (Saynor & Erskine 2006).

Discussion

Work on bedload flux and a sediment budget will be finalised during 2005–2006. This will complete the assessment of stream channel characteristics of the Ngarradj ctachment. Even prior to the completition of this last project, sufficient information has now been collected on channel stability of the Ngarradj catchment to reliably determine whether any geomorphic changes occur in the future. The results of this study show that the gemorphic processes operating in the Ngarradj catchment have not been impacted on or accelerated as a result of the construction of the project area at Jabiluka, although the wet season rainfall has generally been above average.

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Gully initiation near the Jabiluka project area

MJ Saynor, WD Erskine[1], KG Evans & I Eliot[2]

Introduction

This research assesses the significance of vehicular traffic as a major process of gully initiation on the sandy footslopes below the Jabiluka project area. Duggan (1988) found that gullies up to 1 m deep have formed during one wet season on disturbed slopes <2° in the seasonally wet tropics of the Kakadu region. Vehicular traffic and cattle and buffalo tracks damage vegetation and destroy protective gravel lags causing gully development (Williams 1976, Duggan 1988, Skeat et al 1996, Saynor et al 2006). The area surrounding the Jabiluka project area exhibits very shallow sands on steep slopes, shallow red or brown uniform sands at the base of bedrock outcrops and deep uniform sands on the footslopes (Bettenay et al 1981). Channels draining the Jabiluka project site are discontinuous, unstable, seasonal streams, devoid of riparian forest (Erskine et al 2001). Gully erosion occurs by nickpoint initiation, upstream nickpoint retreat and subsequent bank erosion of the incised sections (Erskine et al 2001). The studied chanel, Tributary North (fig 1), now has an extensive gully network immediately upstream of the confluence with the main stream, Ngarradj.

Results

Air photograph interpretation showed vehicular track development between 1964 and 1975 through a vegetated swale that then characterised Tributary North. Flow concentration and soil disturbance in wheel ruts caused localised erosion which developed into two gullies (fig 1) after 1982. Erosion had caused the realignment of the track by 1984 and by 1987 gully 1 (fig 1) had formed an integrated channel with Ngarradj. Another track developed in 1998 and, if left unrepaired, may have also initiated gullying where the surficial root mat had been disturbed in a number of severely burnt areas. However, since 1998, track use has been infrequent. In September 1998, an intense fire burnt 10.2 km^2 of the Ngarradj catchment and most of the Tributary North catchment.

The 1998 track was observed immediately after the 1998/1999 wet season (rainfall of 1914 mm). A series of flow-aligned scour holes (Scott & Erskine 1994) had formed in the wheel ruts at two locations on the track. Five holes in the left rut were clustered with two holes in the right rut in a downstream zone 29 m long and another four holes were clustered in the left rut further upstream in a zone 9.5 m long. Approximately 1 m^3 (1.49 t) of sediment was eroded along a distance of 40 m. During the 1999/2000 (rainfall of 2047 mm) and the 2000/2001 wet seasons (rainfall of 1897 mm), the scour holes remained stable following grass colonization. To ascertain why scour hole erosion was initiated on the track rather than elsewhere in grassed depressions, soil characteristics of the track and adjacent areas to a depth of 125 mm were determined (Saynor et al 2004).

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[1] Formerly SSD; now Centre for Sustainable Use of Coasts & Catchments, School of Environmental and Life Sciences, University of Newcastle, Ourimbah Campus, PO Box 127, Ourimbah NSW 2258.

[2] School of Earth and Geographical Sciences, Faculty of Natural and Agricultural Sciences, The University of Western Australia, Mail Drop M004, 35 Stirling Highway, Crawley, Western Australia 6009

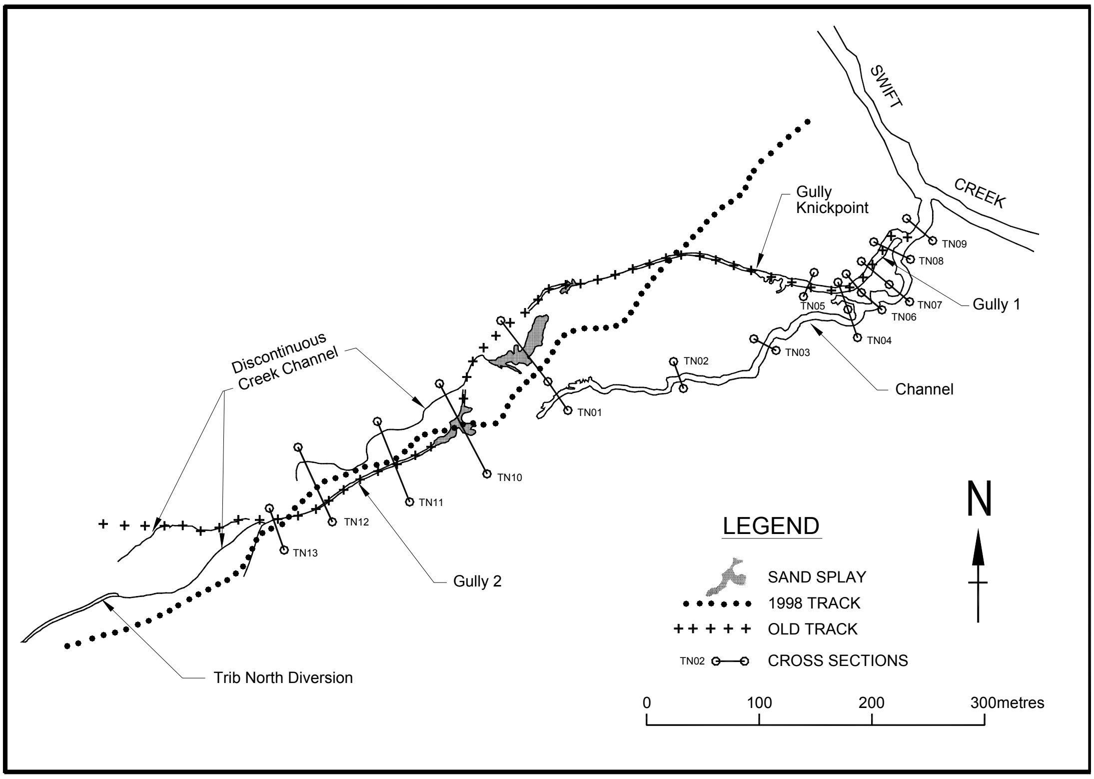

Figure 1 Tributary North showing surveyed tracks, gullies, sand splays and cross sections

The soils are uniformly coarse textured arenic rudosols (Isbell 1996) exhibiting minimal development of a weakly coherent, sandy A_1 horizon over more than 1 m of sandy regolith (C horizon). Roots were common in the A_1 horizon but not at depth. Mean loss on ignition of track surface soils (0–50 mm) was not significantly different from the unburnt areas (ρ = 0.97) but both burnt and unburnt surficial soils exhibited higher mean loss on ignition than the subsurface soils (75–125 mm) ($0.045 > \rho > 0.0012$). Mean bulk density of track surface soil was significantly greater than both unburnt surface soil ($\rho = 0.001$) and unburnt subsurface soil ($\rho = 0.022$) indicating that limited traffic on these sandy soils had significantly increased surficial soil bulk density. Mean root percentages were significantly different between road track surface and undisturbed surface soil ($\rho < 0.05$), indicating that multiple vehicle passes had pulverized and compacted the surficial soil partially breaking down the root mat that was subsequently removed by wet season overland flows.

Discussion and conclusions

Root and algal mats increase soil cohesion, limiting wash erosion and channel incision, and grass vegetation increases critical boundary shear stress for soil erosion (Prosser et al 1995). Vehicular traffic can increase compaction and subsequent erosion rates overriding the effect of erosion-reducing factors (Evans & Loch 1996). The lack of erosion of the scour holes during the wetter 1999/2000 wet season indicated that the combined disturbances of fire and root breaching by vehicles were more important in causing erosion than the amount of overland flow. The coarser sand on the track also predisposed it to erosion when multiple vehicle passes compacted the soil and disturbed the root and algal mats.

Coalescence of the discontinuous scour holes into a gully during subsequent wet seasons did not occur because:

1 vehicles avoided the eroded section and used a new track alignment;

2 grasses regenerated during the wet season following scour hole initiation, re-establishing root and algal mats;

3 an intense, late dry season fire burnt the grassed swales prior to 1998/1999 wet season, before the track was used repeatedly and removed all above ground cover before the first vehicle passes. As a result, vehicles caused greater disruption of the root and algal mats than would have occurred if the grass cover had not been burnt. A similar intensity late season fire has not occurred since the track was formed;

4 the grassed swales are not part of the main channel network and hence only convey episodic overland flows; and

5 vehicular traffic in the area has been greatly reduced since the scour holes were initiated.

The developmental sequence of a gully from a grassed swale via scour holes is reversible. As outlined in figure 2, scour holes can be converted back to grassed swales, provided the process disturbing the grass cover and root and algal mats is quickly identified and removed. The abandonment of the eroded section of the track and the renewed growth of grass during the next two wet seasons resulted in some infilling of the scour holes.

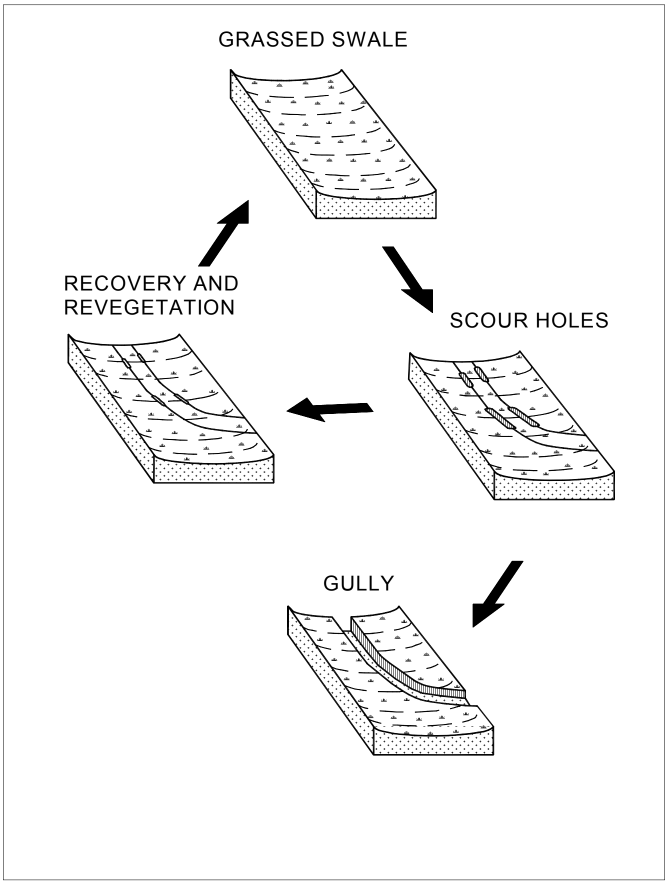

Figure 2 Gully development in grass swales involving a reversible intermediate stage for scour holes

Scour holes are the initial phase of gully development and should be identified and treated before large scale erosion occurs. Gully erosion prevention is better than cure because the greatest sediment yields are generated during the initial growth stage (Graf 1977, Prosser & Winchester 1996, Erskine 2005).

The progression of disconnected scour holes to gullies can be prevented by stopping the continued disturbance of the root and algal mats and by re-establishing the grass cover. The recognition of scour holes as an intermediate step in the development of a gully allows their targetting with soil conservation works and their reversion to a grassed swale. Traffic should also be restricted on sensitive landforms to prevent localised erosion (Evans & Loch 1996).

Acknowledgments

Michael Grabham, Dr Guy Boggs, Dr Max Finlayson, Bryan Smith and Gary Fox are thanked for their contributions.

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Scour and fill in the Ngarradj catchment between 1998 and 2003

MJ Saynor, WD Erskine[1] & KG Evans

Introduction

Two fluvial processes, bank erosion and bed scour and fill, were identified as significant sediment sources during initial field inspections of the Ngarradj catchment before construction of the Jabiluka project area (Erskine et al 2001). Bed scour and fill are discussed in this paper. Actual depths of bed scour and fill during wet season floods are usually much greater than the net changes in bed level measured at the permanently monumented cross sections between successive dry season, discussed by Saynor et al (2006) in this volume. The channel bed is the first temporary sediment storage for any sandy material and possible associated contaminants delivered from the mine to the channel network. The study area characteristics and hydrology are outlined in Saynor et al (2006) in this volume and the location of the study area is shown in figure 1 of Saynor et al (2006). The aim of the work was to determine the amount of scour and fill in the sand-bed streams in the Jabiluka project area.

Methods

Depths of scour and fill during each wet season between 1998 and 2003 were measured by metal scour chains, as developed by Emmett and Leopold (1963), Emmett (1965) and Leopold et al (1966). Thirty scour chains were installed in various channel reaches of the Ngarradj catchment during the late dry seasons of 1998 and 1999. The scour chains were always located on surveyed cross sections to aid recovery (Saynor et al 2001; 2004). The chains were installed so that the top link of the metal chain was level with the channel bed. After each wet season the elevation of the stream bed was resurveyed before the bed was excavated until the chain was exposed. Various measurements were made between the dry season bed level and the scour chain, which were then used to determine the amount of scour and fill that occurred in the previous wet season (Saynor et al 2004). Figure 1 shows the three examples of bed level change that can occur during a wet season. Depth to straightened chain (DSC) is one of the measurements made and is the actual change in bed level between successive dry seasons.

Scour chain results

Data for the scour chain measurements are contained in Saynor et al (2002, 2004a) and detailed results are contained in Saynor et al (2004b). Table 1 shows the average values of net change in scour and fill for each study reach in the Ngarradj catchment for each year of measurement. Net scour is denoted by a negative value and net fill by a positive value.

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[1] Formerly SSD; now Centre for Sustainable Use of Coasts & Catchments, School of Environmental and Life Sciences, University of Newcastle, Ourimbah Campus, PO Box 127, Ourimbah NSW 2258.

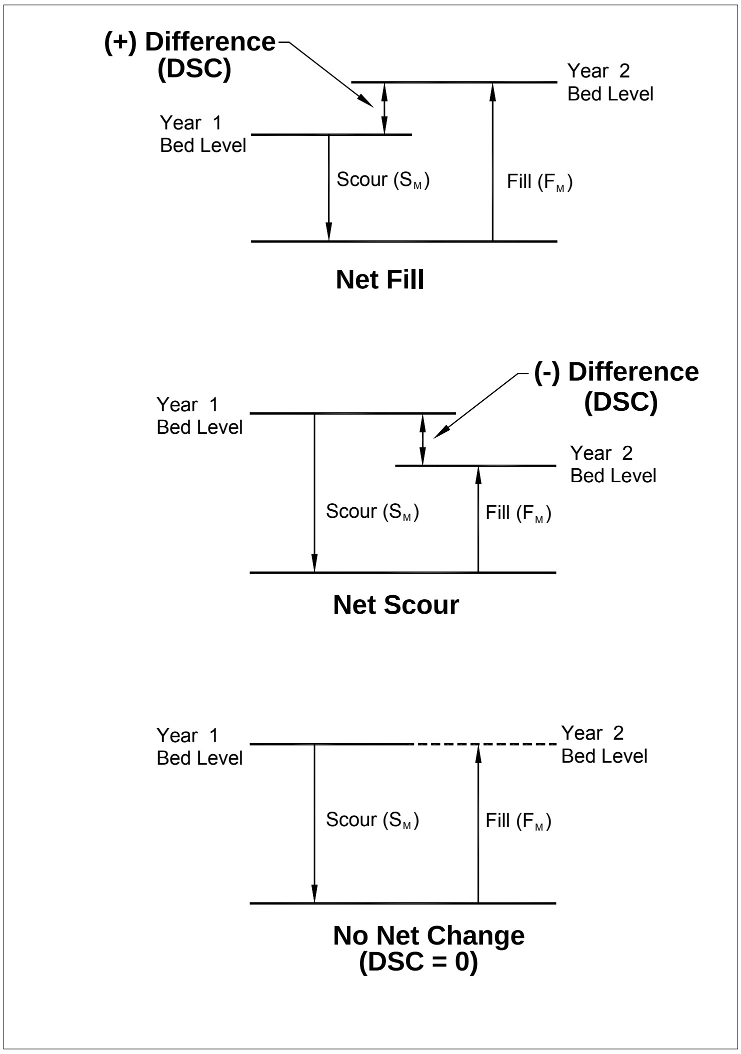

Figure 1 Three examples of net channel bed change during the wet season measured by scour chains. Net fill occurs when the bed level for the 2nd year is higher than for the 1st (top). Net scour occurs when the bed level for the 2nd year is lower than for the 1st (middle). No net change occurs when the bed level for the 1st and 2nd years is the same (bottom).

Table 1 Mean net scour (negative) and net fill (positive) and the standard error of estimate for each reach in which scour chain measurements were made for each wet season. All units are in mm. For location of study reaches, see figure 1 in Saynor et al (2006).

Reach	1998/1999 Scour/Fill	1999/2000 Scour/Fill	2000/2001 Scour/Fill	2001/2002 Scour/Fill	2002/2003 Scour/Fill
Tributary North	Not Installed	25 ± 16	-25 ± 18	-6 ± 25	63 ± 27
Tributary Central	Insufficient Data	-7 ± 23	97 ± 91	-7 ± 29	12 ± 20
East Tributary gauge	32 ± 76	-29 ± 19	2 ± 14	27 ± 24	52 ± 45
Upper Swift Creek gauge	142 ± 41	21 ± 7	14 ± 4	9 ± 7	28 ± 10
Swift Creek gauge	80 ± 8	23 ± 18	0 ± 15	Insufficient Data	-33 ± 24
Average	85 ± 28	7 ± 11	18 ± 21	6 ± 8	24 ± 17

Except for the 1998/1999 wet season for which there is the least data, both net scour and net fill were recorded in the study reaches for each wet season. The mine site tributaries alternated between net scour and net fill over 1–2 year time periods. Net fill dominated in the three gauging station reaches. The results of one year measurements of scour and fill, as carried out by Roberts (1991) on Magela Creek, are likely to yield little information on longer term trends and, therefore, one year of measurements is not recommended for future use in the Alligator Rivers Region. Furthermore, given the variance in the scour and fill data, at least 10 chains should be installed in a measurement reach to reliably estimate mean values.

The catchment average net scour and fill was calculated as the arithmetic mean of the averages for each measurement reach (table 1). Alternative weightings could be used, such as one based on reach length. On a catchment scale, fill occurred for all five years. However, the standard error of estimate was large in relation to the mean for all years of measurement, except the first, which had the least data. However, the current data are not sufficiently reliable to preclude net scour. Furthermore, net scour was recorded in at least one measurement reach for all years, except the first.

The scour chain measurements indicate that minor net fill is currently occurring in the Ngarradj catchment and hence the bed is an active sand storage. Therefore, it is essential that effective sediment control measures are maintained on the Jabiluka project area because mine-derived sand will be quickly routed to the channel network where it will be temporarily stored. The scour chain measurements do not indicate that the mine site tributaries (Tributary North and Tributary Central) have been oversupplied with sand derived from the mine site because active bed aggradation is not currently occurring. The data in table 1 have been converted to sediment masses in table 2 by using known measurement reach lengths (Saynor et al 2004b) and a uniform sediment bulk density of 1.5 t/m^3. The scour and fill data indicate that net fill is currently occurring in the Ngarradj catchment (table 2).

Table 2 Mass of sediment (tonnes) stored in channel bed in measurement reaches (+ values) or scoured from the bed (- values). Note that the sign is the opposite of that used in table 1 to be consistent with the scour and fill literature.

Reach	Mass of sediment (tonnes) stored (+) or eroded (-)				
	1998/1999	1999/2000	2000/2001	2001/2002	2002/2003
Tributary North	Not installed	20	-20	-5	51
Tributary Central	Insufficient data	-7	99	-7	12
East Tributary gauge	3	-3	0	3	5
Upper Swift Creek gauge	22	3	2	1	4
Swift Creek gauge	18	5	0	Insufficient data	-7
Average	43	18	81	-2	65

Conclusions

Scour and fill were active geomorphic processes in the Ngarradj catchment between 1998 and 2003 that resulted in the reworking of the sandy bed sediment. Mean scour ranging from a minimum of -6 ± 25 mm on Tributary North during the 2001/2002 wet season to a maximum of -33 ± 24 mm at the Swift Creek gauge during the 2002/2003 wet season was recorded.

Greater values were recorded at individual cross sections. Mean fill ranging from a minimum of 2 ± 14 mm at the East Tributary gauge during the 2000/2001 wet season to a maximum of 142 ± 41 mm at the upper Swift Creek gauge during the 1998/1999 wet season was also recorded. Again greater values were recorded at individual cross sections. Allowing for plus or minus twice the standard error of estimate of the mean, average scour and fill for the scour chains during each wet season in each measurement reach usually overlap with each other. This indicates that mean annual scour and fill were not significantly different. On a catchment scale, fill occurred for all five years. However, the standard error of estimate was large in relation to the mean for all years of measurement. Net scour was recorded in at least one measurement reach for all years, except the first.

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Michael Grabham, Dr Guy Boggs, Dr Max Finlayson, Bryan Smith, Gary Fox and Elice Crisp are thanked for their contributions.

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Cross-sectional changes in the Ngarradj catchment between 1998 and 2003

MJ Saynor, WD Erskine[1] & KG Evans

Introduction

Various fluvial erosion processes were identified as potential sediment sources during initial field inspections of the Ngarradj catchment before construction of the Jabiluka project (Erskine et al 2001). Two of these processes were bank erosion and scour and fill of the sandy creek beds. This paper documents the study of channel change and large-scale bank erosion. To measure the amount of large-scale bank erosion in the Jabiluka project area, permanently marked channel cross sections on the project site tributaries (Tributaries North and Central) and at the three ***eriss*** gauging stations (figure 1 in Saynor et al 2006) were installed. Erosion pins were used to measure small-scale and slow rates of bank erosion in the Ngarradj catchment (Saynor et al 2003, Saynor & Erskine 2006). The study area characteristics and hydrology are outlined in Saynor et al (2006). The aim of the work was to determine changes in channel morphology due to bank erosion in the sand-bed channels on the Jabiluka project area that may be due to project site disturbance.

Methods

Fifty-six permanently monumented channel cross sections were installed throughout the Ngarradj catchment during the 1998 dry season, following the approach of Miller and Leopold (1963) and Leopold et al (1966). Multiple cross sections were installed at each gauging station (upper Swift Creek, Swift Creek and East Tributary) as well as on the mine site tributaries, Tributary North and Tributary Central (fig 1 in Saynor et al 2006). Site-specific details of the ***eriss*** research program in the Ngarradj catchment are provided by Saynor et al (2001). The cross sections were surveyed annually during each subsequent dry season to 2003 to determine the net change during each intervening wet season. Repeated surveys of permanently marked cross sections only measure the net change between successive wet seasons. The actual depths of scour and fill during floods are usually much greater (Emmett & Leopold 1963, Leopold et al 1966) and are discussed in Saynor et al (2006) in this volume. The cross sections were also used to determine bankfull hydraulic geometry parameters (width, mean depth, area, mean velocity, bankfull discharge and specific stream power) for each survey and changes in channel geometry between surveys.

The data for the annual cross section surveys in the Ngarradj catchment between 1998 and 2003 are presented in Saynor et al (2002, 2004a). Figure 1 shows an example of a cross section plot from Ngarradj and all cross section plots are shown in Saynor et al (2004b). Where changes in hydraulic geometry parameters between 1998 and 2003 are less than ± 1%, the section is called stable.

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[1] Formerly SSD; now Centre for Sustainable Use of Coasts & Catchments, School of Environmental and Life Sciences, University of Newcastle, Ourimbah Campus, PO Box 127, Ourimbah NSW 2258.

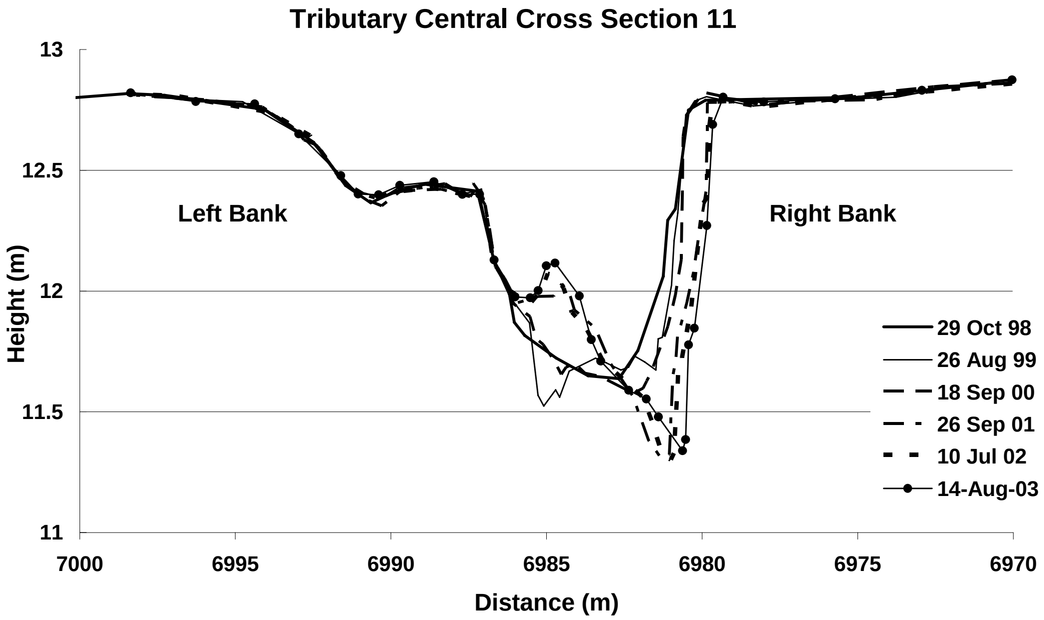

Figure 1 Tributary Central cross section 11

Results and conclusions

Cross section surveys were used to derive the channel hydraulic parameters for each year between 1998 and 2003, and summarised in table 1.

Integrating the data from table 1 for the six years 1998 to 2003 indicates that:

- The lower gullied section of Tributary North which, is integrated with the main Ngarradj channel, is developing by upstream migration of the primary nickpoint and subsequent channel widening and bed degradation. Aerial photograph interpretation (Saynor et al 2004b) indicated that these geomorphic processes were occurring before the development of the Jabiluka project area and their rates of activity have not been accelerated since the project site was developed.
- Channel erosion by lateral migration, bed degradation and channel widening are active on Tributary Central. Air photograph interpretation indicated that these recent channel changes were initiated between 1950 and 1964, and rapidly developed up to 1975 (Saynor et al 2004b). The above geomorphic processes were not initiated by the Jabiluka project area.
- The percentage changes in hydraulic geometry parameters since 1998 at the East Tributary gauge are much less than on the project site tributaries, because of the stabilising effects of the monsoonal gallery forest.
- The upper Swift Creek gauge is currently aggrading due to the supply of sand from the upstream catchment, probably from a combination of channel erosion and soil erosion of episodically burnt areas.
- The Swift Creek gauge has also aggraded since 1998. This sand has been mainly supplied from the upper catchment because upper Swift Creek is also aggrading, because the sand from Tributary Central is completely stored before reaching Ngarradj and because Tributary North only supplies small volumes of sand to Ngarradj.

Table 1 Changes in various hydraulic geometry parameters between 1998 and 2003. The percentage value in the brackets indicates the maximum change.

Hydraulic geometry parameter	Tributary North main gully	Tributary North tributary gully	Tributary Central	East Tributary	Upper Swift Creek	Swift Creek
Number of cross sections	8	5	14	8	8	8
Cross-sectional area	Decreased at 3 (3%) Increased at 4 (16%) Stable at 1	Decreased at 2 (5%) Stable at 3	Decreased at 2 (30%) Increased at 11 (46%) Stable at 1	Decreased at 1 (2%) Increased at 7 (12%)	Decreased at 8 (10%)	Decreased at 5 (10%) Stable at 3
Width	Increased at 7 (21%) Stable at 1	Increased at 4 (20%) Decreased at 1 (3%)	Decreased at 3 (10%) Increased at 9 (45%) Stable at 2	Decreased at 1 (2%) Increased at 7 (6%)	Decreased at 1 (3%) Increased at 5 (5%) Stable at 2	Decreased at 1 (4%) Increased at 5 (14%) Stable at 2
Mean depth	Decreased at 6 (6%) Increased at 2 (8%)	Decreased at 5 (15%)	Decreased at 5 (18%) Increased at 5 (23%)	Decreased at 2 (4%) Increased at 5 (9%) Stable at 1	Decreased at 8 (11%)	Decreased at 6 (17%) Increased at 1 (1.1%) Stable at 1
Maximum depth	Increased at 7 (31%) Stable at 1	Decreased at 4 (10%) Stable at 1	Decreased at 3 (4%) Increased at 11 (38%)	Decreased at 1 (17%) Increased at 6 (25%) Stable at 1	Decreased at 8 (14%)	Decreased at 7 (17%) Increased at 1 (3%)
Mean velocity	Decreased at 4 (2.8) Increased at 2 (4.7%) Stable at 1	Decreased at 5 (12%)	Decreased at 5 (17%) Increased at 7 (13%) Stable at 2	Decreased at 3 (3.5%) Increased at 5 (6.3%)	Decreased at 8 (8.5%)	Decreased at 6 (12%) Increased at 1 (1.3%) Stable at 1
Bankfull discharge	Decreased at 4 (5.3%) Increased at 4 (16%)	Decreased at 5 (11%)	Decreased at 3 (41%) Increased at 11 (565%)	Decreased at 1 5.3%) Increased at 7 (19%)	Decreased at 8 (15%)	Decreased at 7 (18%) Stable at 1
Specific stream power	Decreased at 6 (7%) Increased at 2 (11%)	Decreased at 5 (25%)	Decreased at 5 (36% Increased at 9 (33%)	Decreased at 2 (7.3%) Increased at 5 (17%) Stable at 1	Decreased at 5 (20%) Stable at 3	Decreased at 6 (26%) Increased at 1 (3.1%) Stable at 1

The survey data were also used to calculate changes in sediment storage for each measurement reach and for all reaches combined for each wet season between 1998 and 2003 as well as for the complete period. The channel network was a net sediment source due mainly to high rates of channel erosion in Tributary Central. However, this sediment is stored upstream of the Ngarradj main channel.

Acknowledgments

Michael Grabham, Dr Guy Boggs, Dr Max Finlayson, Bryan Smith, Gary Fox and Elice Crisp are thanked for their contributions.

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Part 4: Nabarlek

Contents[1]

[1] List of papers grouped by Key Knowledge Need.

Vegetation monitoring techniques at Nabarlek mine site using remote sensing and ground-based studies

K Pfitzner

Introduction

Nabarlek is the first uranium mine in Australia to be rehabilitated under a contemporary regulatory regime and, hence, exemplifies many issues highly relevant to the future rehabilitation of Ranger mine. ARRTC in 2003 identified the following three key research issues with respect to the revegetation component of rehabilitation of uranium mines in the ARR that need to be addressed:

- what are the criteria for assessing revegetation success?
- what are the indicators of success and how do we monitor them?
- what can we learn from Nabarlek?

The aims of this project are to (i) develop cost-effective ground-based and remote sensing monitoring and assessment methods for vegetation that can be applied to Ranger uranium mine; and (ii) to provide a robust, quantitative assessment of the success of revegetation at Nabarlek based on a comprehensive characterisation of soils and plants across the minesite in comparison to adjacent reference or analogue sites.

Field-based transect sampling for canopy cover attributes occurred in the dry season (September 2003), and the combination of the dry and wet season (April 2004) surveys established the base line for ground cover attributes. Additionally, a base line for soil properties was established in the first dry season survey, and an assessment of nutrient cycling and the soil seed bank were undertaken in the wet season survey. In conjunction with the ground-based studies, remotely sensed data from DigitalGlobe's Quickbird satellite platform were captured in both seasons to provide a 'whole of landscape assessment' to overcome under-sampling problems associated with the ground-based surveys. Another image capture was acquired in August 2004 to assess the effects of a fire that occurred on the site (July 2004). Further ground-based studies with a dGPS were undertaken aimed at sampling homogenous patches of cover for correlation with the remotely sensed data and for accuracy assessment of these results.

Progress to date

Vegetation has been characterised at the Nabarlek minesite and on adjacent natural reference sites sufficiently to form the first quantitative base line for future monitoring and assessment purposes (Bayliss et al 2004a & b, Bayliss & Pfitzner 2004, Vink 2004). These results showed that revegetation so far remains unsuccessful with respect to the original objective of blending in with the surrounding woodland (Bayliss et al 2004a & b, Bayliss & Pfitzner 2004, Vink 2004).

The periodic flooding of the former Evaporation Ponds can be a hindrance to the establishment of at least *Eucalyptus tetradonta* and *E. miniata* (Vink 2004). Nutrient cycling was found to be established and not a limiting factor in the successful revegetation at the Nabarlek minesite (Manning 2004). Characterisation of the soil seed bank showed a distinct difference between the disturbed and undisturbed sites, with a high number of weed seeds present on the minesite indicating that the revegetation in its present state is not sustainable (Manning 2004). The contrast in soil and vegetation characteristics was so great that the limited ground-based sample size (n=12 transects on the minesite, 0.17% of rehabilitated area; n=6 transects on reference sites) was considered to have sufficient power for medium term monitoring purposes (Bayliss et al 2004a & b).

Expectations that the ~2.5 m multispectral Quickbird data could be integrated with the ~60 cm panchromatic data to produce a 'pan-sharpened product' maintaining spectral range at the smaller pixel size were false, given the data quality supplied by Sinclair Knight Merz (SKM). After discussion at the North Australian Remote Sensing and GIS Conference (Pfitzner 2005), a teleconference between the information providers (DigitalGlobe, Colorado), information resellers (SKM, Melbourne) and SSD, resulted in the agreement for DigitalGlobe to provide demonstration orthorectified data using the University of New Brunswick (UNB) pan-sharpening algorithm that produced image data maintaining the spectral range at the 60 cm pixel size. With the four spectral dimensional limitations of Quickbird data, a contextual program (eCognition) is being implemented, and these algorithms are being applied to the UNB product for each of the three data captures.

Other remotely sensed data, such as Compact Airborne Spectrographic Imager (CASI) has shown promise for revegetation assessment at Nabarlek (Pfitzner & Martin 2003, Pfitzner et al 2004), but these data have only been assessed for a one-off capture (June 2002). HyMap (September 2002) and DeBeers Hyperspectral data (June 2004) have also been acquired over Nabarlek for the purposes of assessing the suitability of high spectral resolution data for revegetation assessment.

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Assess a variety of spatial, spectral and temporal scaled remotely sensed data for rehabilitation assessment

K Pfitzner

Introduction

A variety of remotely sensed data have been acquired by SSD. Examples include: Compact Airborne Spectrographic Imager (CASI) (Nabarlek, Rum Jungle), DeBeers Hyperspectral Mapper (Ranger, Nabarlek and Rum Jungle) and temporal Quickbird data (Nabarlek). In addition, airborne gamma ray data have been acquired at varying line spacings (Nabarlek, upper South Alligator River valley, Sleisbeck). Fieldwork was undertaken with each acquisition. These data were acquired to assess the suitability of remotely sensed data for minesite assessment, both for operational and rehabilitated mine surfaces.

Until recently, identifying relationships between biophysical variables and electromagnetic radiation has been limited for minesite applications due to the disturbed nature of the mine environment and small areal extent. Recently, newer generation remote sensing data are being trialled in the mine environment, with results depending on the sensor being assessed and the localised environmental conditions. Prime applications include: revegetation and soil mapping for rehabilitation assessment; mineral mapping, such as identifying indicators of acid mine drainage (AMD) processes; and, contribution of remotely sensed data for radiological assessments. Airborne data are currently advantageous with suitable spatial, spectral and radiometric resolutions, although temporal availability is a limitation. Satellite data can be timed with field surveys, however, spectral resolution is a current limitation.

The opportunistic remotely sensed data that have been acquired to date are being assessed for their cost/benefit and suitability of spectral, spatial and temporal characteristics on a site-by-site basis. Once existing data have been analysed, this project will use an analysed ground-based spectral library database to make recommendations on suitable remotely-sensed data for minesite rehabilitation assessment; acquire simultaneously a variety of spatial, spectral and costed datasets, as seen suitable by the ground-based database; analyse and quantitatively compare such data; perform a cost-benefit analysis, and publish results.

Progress to date

CASI has shown promise for both revegetation assessment at Nabarlek (Pfitzner et al 2004a, Pfitzner & Martin 2003a), and mapping mineral assemblages indicative of AMD (Pfitzner 2004, Pfitzner & Clifton 2004, Pfitzner 2005a), but these data have only been assessed for a one-off capture (June 2002). Hymap (September 2002) and DeBeers Hyperspectral data (June 2004) have also been acquired over Nabarlek and Ranger for the purposes of assessing the suitability of high spectral resolution data for revegetation assessment.

Quickbird data have been applied at Nabarlek for vegetation characterisation (Pfitzner 2005a) and at Ranger for weed mapping (Pfitzner et al 2004b, Welch et al 2004) (for details see KKN research summaries 4.4.1 and 2.5.1, respectively).

Airborne gamma-ray analysis at the upper South Alligator River valley is complete (Pfitzner & Martin 2000, Pfitzner et al 2001a & b, Pfitzner & Martin 2003b, Bollhöfer et al 2002, Pfitzner 2005b) and a journal manuscript has been published (Pfitzner 2005c).

To make informed decisions about the most appropriate dataset for a given problem, a knowledge-base describing the relationship between spectral reflectance and the chemical and physical properties of biophysical features of interest are required. SSD aims to develop a spectral library of land cover components in order to make recommendations on suitable remotely sensed data for minesite rehabilitation assessment and monitoring. An Analytical Spectral Device (ASD) FieldSpec Pro FR unit was received on 12 April 2005. A literature review has been conducted to describe, in simple terms, the components for consideration when developing an effective field campaign and database for the storage of spectral information and associated metadata. Pfitzner et al (2005) describe the factors that affect standardised reflectance spectra and issues for consideration are presented as a conceptual model. The spectral library research design has also been presented to the Spatial Sciences Institute Northern Territory Region ('The hype and hyper of hyperspectral remote sensing and field spectroscopy', Survey House, Engineers Australia, Darwin, 11 May 2005) and the North Australian Remote Sensing and GIS Conference (Pfitzner 2005b).

With cooperation from Gary Cook and Rob Eager (CSIRO), Graeme Webb (Crocodylus Park), Bruce Sawyer (Berrimah Farm), Peter Hopkins (Coastal Plains Research Station), Les Huth (Beatrice Hill Agricultural Research Station), Peter Clifton (DPIFM), and Mark Gardener and Jane Addison (EWLS), sites suitable for temporal field measurement covering a range of native and weed grass and herb covers have been targeted. SSD's Analytical Spectral Device (ASD) is being used to measure reflectance of weedy and native ground covers across the visible to shortwave-infrared (0.4–2.5 µm) region at fortnightly intervals around the sites in the greater Darwin region to capture environmental variation in reflectance.

A spatio-temporal campaign, implementing the metadata design outlined in Pfitzner et al (2005), was conducted at Nabarlek on 8 June. Only two hours of operation were available due to a manufacturing fault. In this time, 750 spectra of *Urochloa mutica*, 250 spectra of *U. mutica* / *Aeschynomene american*, and 125 spectra of *Cynodon dactylon* were recorded (see figure 1). Based on Pfitzner et al (2005) appropriate metadata were also recorded. The faulty spectrometer was returned to Analytical Spectral Devices Inc, Boulder, Colorado, on 22 June and received back on 15 July. A part-time, non-ongoing Technical Officer is assisting with the collection, processing and analysis of spectral information.

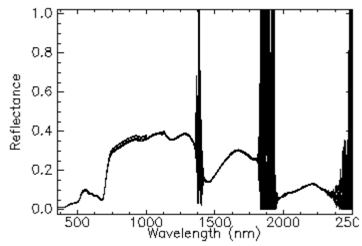
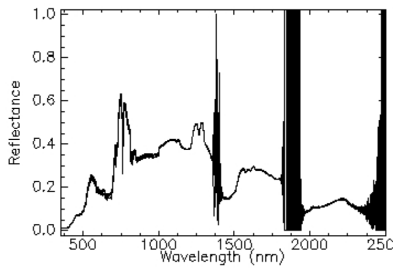
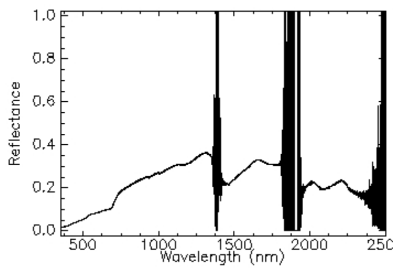
Name and brief description	Averaged spectra – 25 AVERAGES /SAMPLE
U. mutica Para grass, monoculture, 90% green, 10% senescing	
U. mutica and *A. american* Para grass (35% brown, 15% green) and *A. Americana* (50%)	
C. *dactylon* Couch, monoculture, 80% brown, 20% green	
Note: water vapour absorption bands occur at ~1400 and 1900 nm. System noise at 2450 nm	

Figure 1 Examples of spectra obtained at Nabarlek 08/06/2005

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Sediment and radionuclide fluxes from the former Nabarlek mine

GR Hancock[1], MK Grabham[1], P Martin[2], KG Evans & A Bollhöfer

Introduction

The Nabarlek mine site lies within the catchments of the Cooper Creek West (CCW) (181 ha), Buffalo Creek (BC) (575 ha) and Kadjirrikamarnda Creek (KC) (2188 ha) (fig 1). The mine disturbs 1.6%, 0.6% and 0.6% of the catchments respectively. These three catchments drain into Cooper Creek, which in turn discharges into the mouth of the East Alligator River. Cooper Creek drains 25 238 hectares at its confluence with Kadjirrikamarnda Creek.

This project used field and laboratory data and modelling techniques to determine sediment and radionuclide fluxes passing from the site to assess impacts on water quality in Cooper Creek.

Results

Gross erosion occurring on the Nabarlek site was determined using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al 1994). The site was initially divided into homogeneous sub-areas, or erosion units, based on visual differences identified from stereoscopic interpretation of photographs and topographic maps (fig 2). This identified changes in soil colour, vegetation cover, ripped areas and vegetation assemblage. Confirmation or alteration of boundaries was undertaken by ground truthing. Field data (permeability, soil particle size, soil structure, vegetation cover) for input parameter value derivation were collected from each unit.

The gross erosion occurring on each erosion unit was calculated and the results added to provide a gross sediment loss estimation for the site. Sediment loss from the Nabarlek site was assessed under vegetation and burnt conditions.

Soil samples collected from the main identified erosion units were analysed by high-resolution gamma-ray spectrometry. This technique gives simultaneous measurements of mass activity densities (Bq kg^{-1}) of a number of radionuclides of the uranium and thorium radioactive decay series, as well as ^{40}K, in the sample (table 1). These data were then multiplied by the estimates for delivery of eroded soil to the Cooper Creek system to give an estimate for the radionuclide flux passing from the site to downstream waterways from each erosion unit.

The results showed that predicted gross erosion on the Nabarlek site is higher than that occurring on natural areas of the catchment. However, the results show the site to be eroding at a rate close to that predicted by Riley (1995) using the USLE, providing confidence in our results.

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[1] School of Environmental & Life Sciences, The University of Newcastle, Callaghan, New South Wales 2308, Australia.

[2] Formerly SSD; now Agency's Laboratories Seibersdorf, IAEA, A-1400, Vienna, Austria.

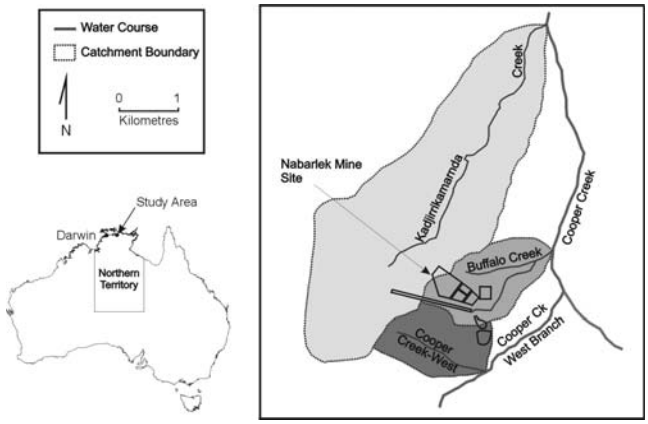

Figure 1 Catchment division on the Nabarlek mine

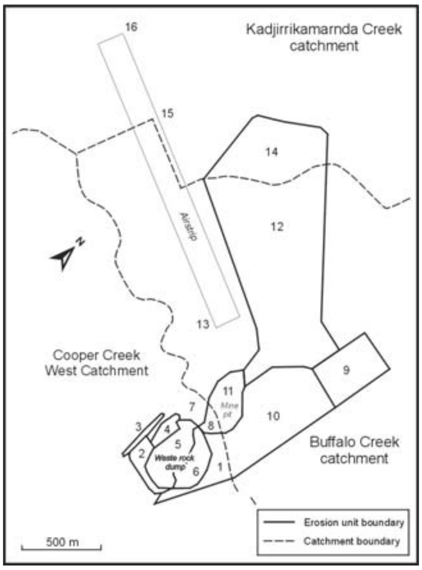

Figure 2 Location of erosion units (numbers) on the Nabarlek mine

This suggests that the rehabilitated landscape will maintain its integrity for the recommended design life of 1000 years (Commonwealth of Australia 1987). Furthermore, the estimated suspended sediment concentrations for unvegetated conditions do not exceed the local trigger values derived in accordance with the water quality guidelines. However, stream sediment loads in the catchments draining the Nabarlek site – Cooper-west, Buffalo and Kadjirrikamarnda Creeks – may have elevated concentrations. The increased sediment concentration predicted for these catchments were based on non-vegetated conditions and therefore represent a worst case scenario. It is highly unlikely that an entire catchment such as CCW could be razed of vegetation, giving rise to such high levels of sediment loss.

Erosion unit 7 has been identified as the dominant source of radionuclide fluxes (74%) from the site under measured (vegetated) conditions (table 1). Given the small (0.44 ha) size of this unit, it would be possible to achieve significant reduction in the fluxes from the site with a relatively modest further rehabilitation effort.

Details of this study are available in Hancock et al (2006).

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Table 1 Radionuclide mass activity densities[1] (Bq/kg dry weight) for surface soil samples, and the estimated % contribution to the total ^{238}U flux to the Cooper Creek system from each of the erosion units for measured conditions

Er. unit	*n*	^{238}U (Bq/kg)	^{226}Ra (Bq/kg)	^{226}Ra range (Bq/kg)	^{210}Pb (Bq/kg)	^{228}Ra (Bq/kg)	^{40}K (Bq/kg)	% flux ^{238}U
13	3	48 (16)	67 (19)	45 – 79	110 (9)	24 (4)	18 (7)	9.1
15	3	53 (34)	58 (38)	21 – 97	90 (8)	28 (9)	61 (12)	3.1
16	7	64 (57)	60 (51)	21 – 145	78 (60)	23 (6)	83 (101)	0.07
3	2	64 (21)	92 (47)	58 – 125	108 (60)	34 (7)	123 (24)	0.7
14	6	104 (71)	101 (77)	51 – 249	117 (78)	24 (7)	62 (109)	0.14
1	3	138 (101)	292 (219)	39 – 437	292 (218)	24 (5)	48 (35)	0.4
2	3	175 (28)	192 (20)	178 – 215	191 (71)	42 (3)	211 (84)	0.01
9	2	177 (95)	168 (85)	108 – 228	177 (66)	31 (2)	110 (110)	0.3
10	4	263 (168)	330 (205)	177 – 629	348 (226)	36 (10)	130 (16)	3.2
12	6	353 (337)	340 (341)	104 – 999	340 (325)	47 (25)	281 (317)	2.0
6	2	496 (105)	497 (132)	404 – 591	538 (177)	79 (41)	790 (454)	0.6
5	4	801 (396)	767 (367)	272 – 1060	780 (324)	108 (18)	1120 (300)	0.15
8	4	1320 (880)	1540 (840)	330 – 2260	1520 (950)	83 (11)	860 (309)	0.009
4	3	2460 (610)	2540 (730)	1980 – 3370	2620 (850)	108 (25)	1120 (330)	6.1
11	6	2530 (1290)	2380 (930)	1160 – 3450	2330 (790)	100 (20)	1110 (260)	0.09
7	6	6780 (4780)	15400 (8400)	1690 – 23900	19100 (10200)	42 (16)	222 (49)	74

[1] Results are given as the mean for the n samples, with the standard deviation in brackets.

Assessing the geomorphic stability of the rehabilitated Nabarlek mine using landform evolution modelling

JBC Lowry, DR Moliere, GS Boggs[1] & KG Evans

Introduction

A joint project with Charles Darwin University (CDU) integrated the SIBERIA landform evolution model and the ArcView desktop GIS software packages through an interface known as ArcEvolve (Boggs 2003), using the the Jabiluka mine within the Ngarradj catchment as a case study. In order to ensure that the knowledge gained from this project was retained within SSD, the software was used by SSD staff to assess the geomorphic stability of the Nabarlek mine as a desktop exercise during 2004–05. The project had three aims:

1 to assess the application of ArcEvolve to a small mine-impacted catchment

2 to predict the surface stability of the catchment areas affected by the Nabarlek mine and possible future impacts; and

3 produce a detailed description of the processes and methods used, for the future application of ArcEvolve to medium-scale catchment areas.

Progress to date

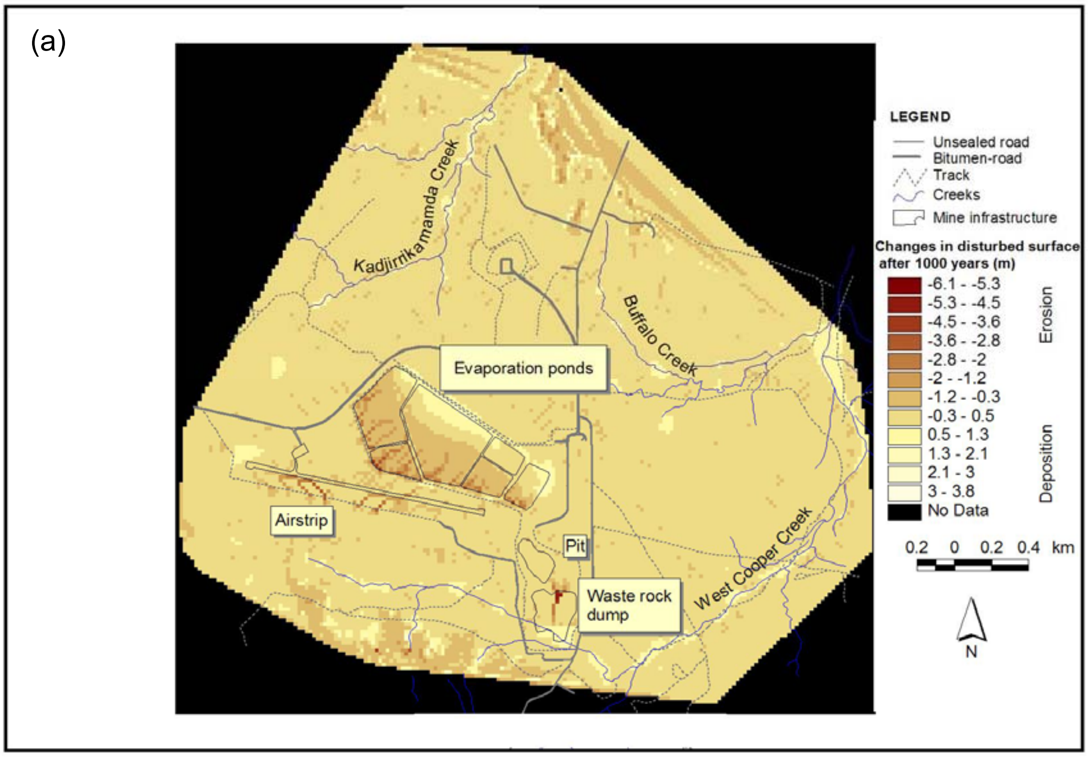
A detailed description of the methods used in the application of the ArcEvolve software to the Nabarlek minesite has been produced as an internal report (Lowry et al 2004).

Using the methodology described in Lowry et al (2004), the draft landform was modelled for a period of 1000 years, with hydrology parameters held constant for the entire landform and erosion parameters varied for each region of the landform representing different surface treatments. Through the GIS interface, it was possible to identify areas of potential erosion/deposition by subtracting the 1000-year modelled surface from the current surface (figure 1). Figure 1a shows the simulated erosion and deposition that occurs on the Nabarlek catchment area at 1000 y using input parameter values derived for the various surface conditions that exist on the landform. For impact assessment, this was compared to the simulated erosion and deposition on the Nabarlek landform assuming natural, undisturbed conditions (figure 1b).

A preliminary assessment was made on the surface stability of the catchment areas affected by the Nabarlek mine using ArcEvolve. The majority of the sediment movement on the rehabilitated landform over a 1000-year simulation period occurred on the evaporation ponds, the waste rock dump (WRD) and the areas adjacent to the airstrip (figure 1). However, the eroded material from these areas was deposited immediately downstream of their respective areas and, therefore, remained on the mine site. As a result, it is unlikely that there will be an immediate mine-derived increase in sediment movement downstream of the mine site. In

[1] Formerly SSD; now Faculty of Education, Health & Science, Charles Darwin University, Darwin NT.

terms of sediment movement and subsequent impacts downstream of the mine, it is considered that the rehabilitated landform is relatively stable over the long term.



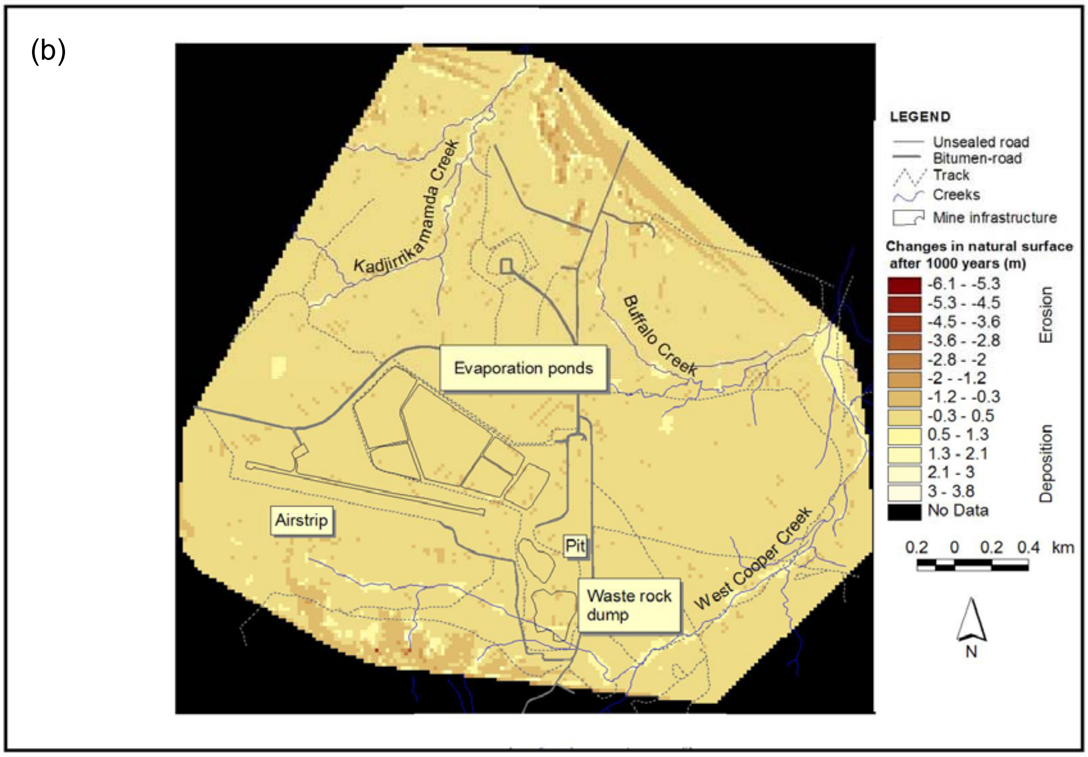


Figure 1 Areas of potential erosion (dark colours) and deposition (lighter colours) on landform after 1000 years using parameters for (a) disturbed conditions; (b) natural conditions

However, as a result of this case study, we identified that the process was unable to assign different hydrology parameter values to the different surface conditions within the catchment area. Therefore, the simulation results for the Nabarlek catchment area (figure 1a) only provide a preliminary assessment of likely landform stability and should not be considered reliable to provide a quantitative estimate of sediment movement in the region. As a result, a secondary aim of this project was to incorporate individual hydrological parameter values into the SIBERIA model to further refine the assessment. This issue is being addressed in the 2005–06 workplan. Specifically, it will be determined whether the above limitation is a result of a problem within the GIS interface or the SIBERIA software itself.

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Radiological impact assessment of the rehabilitated Nabarlek site

A Bollhöfer, B Ryan, P Martin[1] & K Pfitzner

Introduction

There is no permanent habitation close to the rehabilitated Nabarlek uranium mine site at present, but future occupancy of the site cannot be ruled out. Radiological risk assessment, including all exposure pathways, is needed for planning purposes and to achieve closeout of the site. A radiological dose assessment requires integration of sub-tasks such as:

1 Gamma dose rate surveys,

2 Radon exhalation rate and airborne radon concentration surveys,

3 Radionuclide concentration in surface soils and erosion/stability assessment,

4 Bore water uranium isotope and radium concentration measurement, and

5 Measurement of radionuclide uptake into edible plants growing on and off site.

Sub tasks 1, 2 and 3 are mostly complete, and results have been published (Bollhöfer et al 2004, 2005, Hancock et al 2005, Martin et al 2005).

Groundwater contaminant sources on the Nabarlek mine site include the irrigation areas, the previous evaporation and run off ponds, and since rehabilitation the tailings and plant material buried in the pit. An earlier study conducted by ***eriss*** has shown that radium concentration increased in bores in the vicinity of the Nabarlek land application areas during the application period (Martin & Murray 1991). This increase was thought to be caused by mobilisation of radium from adsorption sites on aquifer rocks in the vicinity of the bores rather than radium in the irrigation water.

Methods

Gamma dose rates from the radiological anomalous area (RAA) south of the former pit have been surveyed using conventional Geiger-Müller tubes. The line spacing of the survey amounted to 10–15 m. Radon exhalation had been measured, using a randomised design. Charcoal canisters were deployed for ~3 days and measured for the activity of radon progeny adsorbed onto the charcoal, using a NaI(Tl) gamma spectrometer. Control and environmental sites were investigated throughout the project for quality assurance purposes.

Bore waters have been collected by DME for ***eriss*** since 1996 and aliquots for radioanalysis have been taken for and archived by the Environmental Radioactivity section. Uranium and radium analyses via alpha spectrometry of the samples began in 2004 using standard methods (Martin & Hancock 2004, Medley et al 2005). Long-term groundwater data for uranium isotopes and radium may provide information about groundwater quality, movement and

[1] Formerly SSD; now Agency's Laboratories Seibersdorf, IAEA, A-1400, Vienna, Austria.

sources of contamination. A collaborative project has been started with the Gunbalanya Community Rangers looking for bush foods growing on site.

Results

The site has been characterised from an airborne gamma survey for the external gamma pathway and Table 1 shows the gamma dose rates determined for the various areas on site (Martin et al 2005). Dose rates from the RAA could not be resolved due to its relatively small extent and the resolution of the airborne gamma survey. Figure 1 shows external gamma dose rates in micro Grays per hour (µGy/hr) determined during a detailed gamma survey of the RAA in 2005.

Table 1 Post-mining terrestrial-origin γ-dose rate for areas of the Nabarlek site (Martin et al 2005)

Site	Area (ha)	*D* (µGy·hr^{-1})
Pit	4	0.51
Evaporation pond 1	6	0.48
Waste rock runoff pond	1.9	0.47
Waste rock dump	8	0.46
Evaporation pond 2	25	0.37
Plant runoff pond	1.1	0.36
Stockpile runoff pond	4	0.36
Ore stockpile	6	0.24
Plant and offices	6	0.18
Airstrip LAA	10	0.09
Forest LAA	13	0.05
Total fenced area	140	0.31

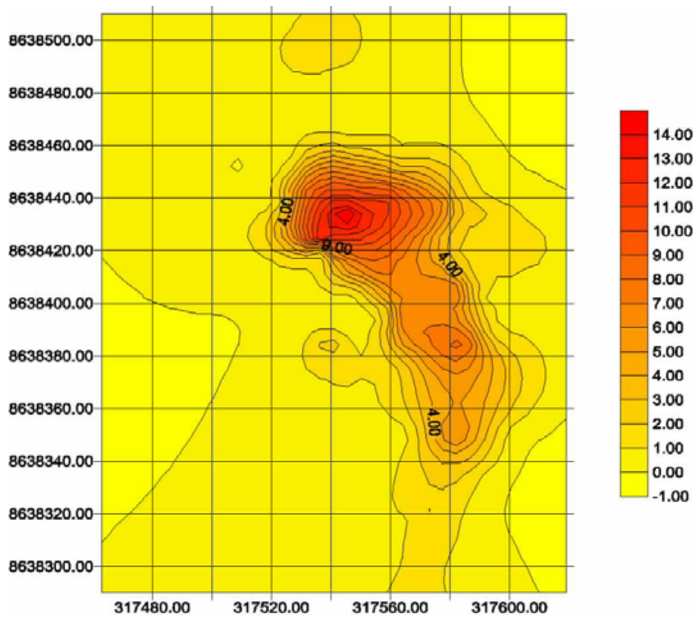

Figure 1 Gamma dose rates [µGy·hr^{-1}] measured at the radiological anomalous area

Maximum dose rates at the RAA are higher than the averages across site, and could inflict a dose on an individual much higher than at other areas. From the field observations and results of the gamma survey it also appears that some material is eroding south east along erosion channels fanning out in a lower lying area on site, south of the former pit area. These results will aid OSS in determining soil coring sites and remediation strategies for the area.

Radon exhalation has been studied in detail and figure 2 shows the results of the study (Bollhöfer et al 2005). The RAA has been identified to contribute about ¼ of the total radon flux from the rehabilitated mine site. Three years of temporal airborne radon data have been acquired and published (Bollhöfer et al 2004) and track etch detectors have been deployed to determine the spatial variation across the site.

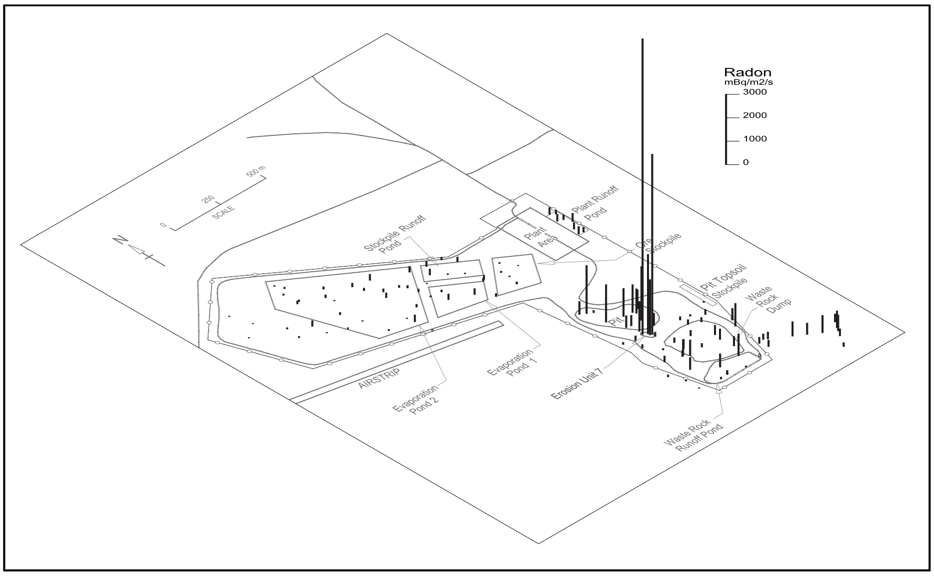

Figure 2 Radon flux densities from surfaces of the rehabilitated Nabarlek mine (Bollhöfer et al 2005)

Bore water samples have been collected by DME in August 2004 and all archived samples have now been analysed for their uranium activity and activity ratios via alpha spectrometry. Generally, uranium activity concentrations are higher in groundwater samples from bores east of the pit and plant areas (OB10, 25, 31) and lower in samples from bores south and west of the fenced area. Interpretation of the full Nabarlek groundwater data set is currently underway.

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Part 5: General Alligator Rivers Region

Contents[1]

[1] List of papers grouped by Key Knowledge Need.

Mangrove response to environmental change, especially climate change

K Pfitzner

Introduction

A collaborative project between the University of New South Wales (UNSW), University of Wales, Aberystwyth, and SSD was established in 2001 to use remote sensing techniques for an analysis of mangrove response to coastal environmental change. The aims of the project were to establish for Kakadu National Park, past and present baselines of mangrove extent, species/community composition, structure and biomass based on, for selected mangroves, a combination of remotely sensed data and field sampling.

Progress to date

Stereo aerial photography, Compact Airborne Spectrographic Imager (CASI) data, and NASA JPL Synthetic Aperture Radar (AIRSAR) data were acquired and investigated for their potential to generate baseline datasets of the extent, height, density, species/community composition and biomass of mangroves within Kakadu National Park.

Stereo aerial photography, acquired in 1991, were used to derive digital elevation models (DEMs) using the procedure outlined by Lucas et al (2002), generating baseline data of mangrove extent (Mitchell et al 2005a & b, Mitchell 2004, Mitchell et al 2003, Mitchell & Pfitzner 2003). Compact Airborne Imaging Spectrometer (CASI) data, obtained over the West Alligator Head Region in 2002, were used to map species composition and assess change in mangrove extent against the 1991 data (Lucas et al 2005, Mitchell 2004) (see figure 1). Radar data from AIRSAR were used to estimate biomass (Mitchell 2004) of the mangrove environment. To support the interpretation of remote sensing data and validation of data products, field measurements relating to the structure, biomass and species/community composition of mangrove forest were required. Anthea Mitchell (UNSW), Kirrilly Pfitzner and Gary Fox (SSD) and Peter Brocklehurst and Chris Mangion (NRETA) conducted one week field sampling at West Alligator Head.

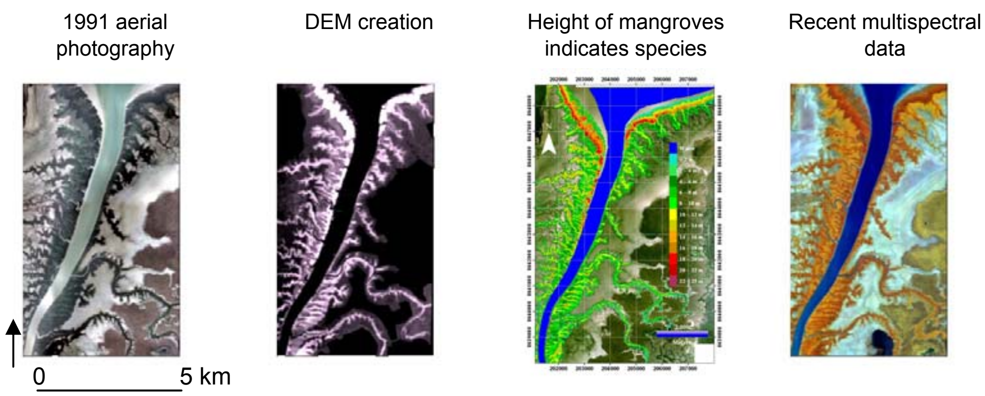

Figure 1 Examples of remotely sensed data of the West Alligator head subset. 1991 stereo aerial photography was used to create a DEM to indicate height of mangrove species (complete for Kakadu National Park). Multispectral CASI data was obtained in 2002 to assess change.

In addition to the references provided, results have been presented at the 2004 International Geoscience and Remote Sensing Symposium (IGARSS04) and 'Mangroves 04' conference. Stakeholders were invited to an SSD seminar on 8 July 2005 for dissemination of results obtained.

In summary, the use of airborne remote sensing data for generating baseline datasets of mangrove extent, height, density, species/community composition and both total and component biomass against which to assess change were demonstrated and a significant and continuing response of mangrove within the ARR to coastal environmental change has been observed (Mitchell 2004).

A meeting was held on 8 July 2005, between Dr Richard Lucas (University of Wales), Dr Anthea Mitchell and Prof Tony Milnes (UNSW), Associate Prof Colin Woodroffe (University of Wollongong) and Dr Kirrilly Pfitzner and John Lowry (SSD) to propose an ARC Linkage grant for further research.

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Ecological risk assessment of Magela floodplain to differentiate mining and non-mining impacts

P Bayliss, R van Dam, J Boyden & D Walden

Introduction

The aims of the 'Landscape-scale analysis of impacts' project is to help differentiate mining and non-mining impacts, and to contribute to the broader assessment of the World Heritage (WH) values of Kakadu National Park (KNP). The analysis framework, underlying conceptual models and quantitative approaches are outlined in detail by Bayliss et al (2003, 2004) and van Dam et al (2004a). This report combines the progress summaries of four projects and is in two parts. Part 1 encompasses an assessment of the condition of, and threats to, susceptible World Heritage values on the Magela floodplain, downstream of Ranger uranium mine. It is basically a first-cut quantitative ecological risk assessment (ERA) of non-mining threats to key WH values. Similarly, Part 2 reports a first-cut quantitative ERA of four key chemical contaminants released from Ranger, and focuses on the surface water pathway mapped out in the conceptual contaminants pathways model (Finlayson & Bayliss 2003, van Dam et al 2004a). A framework is being developed that combines both mining and non-mining ecological risk assessments and is similar to a Bayesian Network (BN). Hence, different degrees of belief with respect to risk, ranging from expert opinion to quantitative estimates derived from frequentist probability models (via probability density functions, pdfs), can be integrated and then communicated with simple influence diagrams and decision trees (see Hart 2004 & @RISK 2002). Stochastic process-based ecosystem models are being developed also to facilitate risk assessment over different time frames and spatial scales. Such models will be driven by rainfall-discharge submodels of the Magela catchment, with direct causal links to the population dynamics of indicator plant and animal species.

Part 1: Landscape

The status of past and current ecological values (assets) and threats on Magela floodplain were mapped in a GIS to facilitate spatially explicit ERAs. Shape-file data layers were converted to raster or grid-cell data format at appropriate levels of spatial resolution (here 250 m x 250 m cells). The spatial and temporal scope of many data sets extend beyond the Magela catchment to include KNP and the ARR in general. An SSR is being drafted that details metadata and data QA/QC protocols associated with all geo-spatial datasets.

Choice of World Heritage values

The two key 'susceptible' WH (& Ramsar) values chosen for assessment are waterbirds (Bellio et al 2004) and wetland vegetation. An assessment of change in their 'condition' was undertaken using spatial and temporal data obtained between 1981 and 2003 (Finlayson 1989 & Lowry et al in prep for vegetation; Bayliss & Yeomans 1990, Morton et al 1990 & PWCNT 2003 for waterbirds). Our initial focus has been on changes in the abundance of 'indicator' species of plants and waterbirds. Future work will examine possible changes in biodiversity. For vegetation we focussed on: weeds; important bush foods of Traditional Owners (eg the red lily); key habitat components of waterbirds for nesting and food (wild rice & *Eleocharis* sedge); and riparian trees susceptible to saltwater intrusion (Melaleucas). For waterbirds, the iconic magpie goose and egrets were chosen for initial analysis because they are the most seasonally abundant plant and fish eaters that use Magela floodplain, respectively. Additionally, the magpie goose is an important part of the diet of Traditional Owners (TOs) in the ARR. Analysis of changes in the distribution and abundance of waterbirds was undertaken using sampling and modelling methodologies developed by Bayliss (1989 & 1990). Long-term changes in fish and aquatic invertebrates communities will be reported in detail at ARRTC16 by C Humphrey and co-workers. Basically, between 1989 and 2005 (16 years) the chequered rainbow fish and two species of glass fish at the Mudginberri monitoring site downstream of Ranger exhibited long-term declines in abundance (13% pa on average) that are apparently unrelated to potential mining impacts. Three key correlates and associated working hypotheses proposed by Humphrey et al (pers comm) that could explain these declines are:

1 increases in mean wet season flow leading to lower water solute concentrations known to be harmful to larval rainbowfishes;

2 decreases in the period of annual drying of the floodplain potentially leading to reduced release of nutrients upon floodplain re-wetting (flood-pulse theory), and thereby reducing fish production in this important breeding and recruitment zone; and

3 increases in the extent of floodplain grasses, including para grass, thereby reducing habitat availability and pathways for upstream migration of fish recruits.

Choice of landscape-scale threats to WH values

Four major categories of landscape-scale threats to the above selected WH values were identified as: invasive species, specifically the wetland weeds mimosa, para grass and salvinia (Walden & Bayliss 2003), and the feral pig (classified as a 'Threatening Process' under the EPBC Act); unmanaged fire; infrastructure; and potential climate change impacts (rising sea level & concomitant salination of freshwater ecosystems, increasing intensity & frequency of storms). Medium to long-term climate change threats, although highly relevant, cannot be adequately addressed in the scope of this study. The ability of wetland weeds to dominate and completely alter aquatic ecosystems has been well documented. The Magela floodplain fortunately remains free of mimosa because of an active 'search and destroy' program by Kakadu rangers, and the impact of the floating fern salvinia has been greatly reduced by biological control. Hence, para grass is the primary focus of our risk assessment of weeds. Ground disturbance damage caused by feral pigs has been ascertained across Kakadu during systematic aerial surveys in 1985, 1995 and 2003 (Bayliss & Yeomans 1990, J Russell-Smith pers comm), and damage to natural and cultural Parks values documented by Whitehead et al (2004). Dry season fire on the Magela floodplain can be viewed either as a cultural asset if part of an Indigenous burning regime, or as a threat if unprescribed by TOs or Park management. To determine which would require detailed ethnoecological knowledge beyond the scope of the present study. However, such a study was completed at the Boggy Plain non-mining reference site as part of the ISP (Independent Science Panel) Landscape program. Infrastructure in the vicinity of the Magela floodplain comprise mostly roads, tracks and fence lines, and these may facilitate the spread of weeds and possibly erosion and siltation. Additionally, the minesite and associated township are sources of weeds for the Magela catchment and Kakadu in general.

Progress

Vegetation

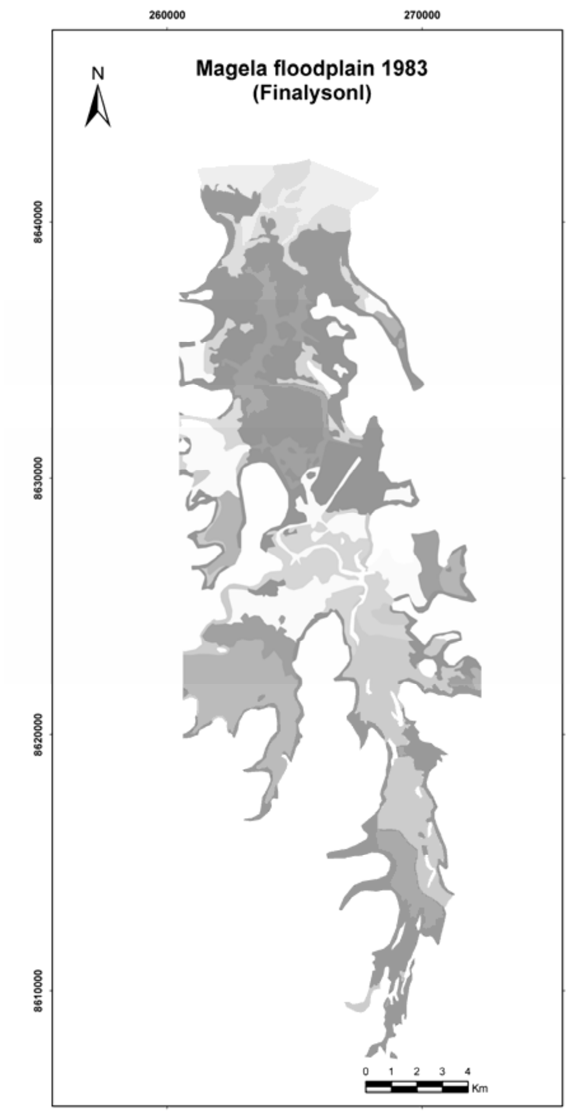
The following eight classes of native vegetation were used to analyse change between 1983 and 2003, representing monocultures that may be less influenced by classification bias: *Eleocharis* spp, *Oryza* spp, *Pseudoraphis spinescens*, *Hymenachne acutigluma*, *Melaleuca* spp, *Nelumbo nucifera*, *Nymphoides* spp and *Leersia hexandra*. Relative change in abundance was measured by change in percentage cover since 1983 (fig 1a & b). Most plant classes changed little except for the following: Nymphoides and Leersia were not recorded in 1983; Eleocharis, an important dry season food of magpie geese, decreased by 57%; Melaleucas decreased by 10%; and Nelumbo decreased by 85%. The 10% relative change in paperbark forest and woodland is significant because on an absolute basis this corresponds to 5km^2 or 3% of the floodplain. Mimosa has been kept under control since the early 1980s through an annual investment (& in perpetuity) of approximately $0.5 million by Kakadu management, and para grass and salvinia have since colonised the floodplain (see fig 1a & b).

Waterbirds

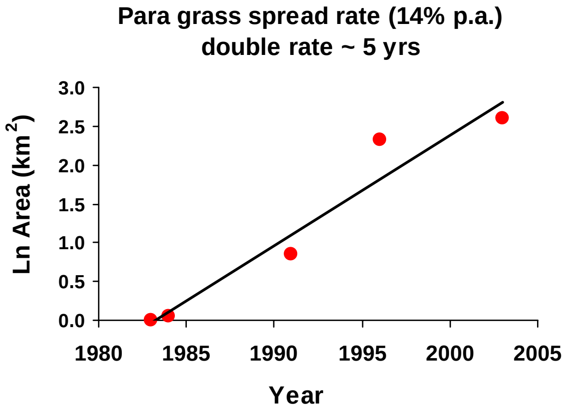
The abundance of magpie geese that occupy Magela floodplain in the late dry season between 1981 and 2003 (22 years) has decreased on average by 7% pa (fig 2c). In the wet seasons of the early 1980s magpie geese used the central portion of Magela floodplain for nesting, an area now occupied by an extensive patch of para grass (figs 1a & b, fig 2a). Additionally, in contrast to the early 1980s, areas now colonised by para grass are used less extensively by magpie geese in the late dry season for feeding (fig 2b). Similarly, fish eating egrets decreased on average by 9% pa since 1981 and also altered their dry season distribution by 2003. However, although the floodplain is about 200 km^2 it is difficult to interpret long-term changes in the abundance of highly mobile waterbird species in isolation from regional and national trends, particularly in relation to anthropogenic changes (see arrows in fig 2c).

Fortunately concurrent national and regional survey data of magpie geese exist, surveys which first commenced in 1958 (Tulloch & McKean 1983) and continued to the present (Bayliss & Yeomans 1990, Saalfeld pers comm). Analyses at increasing spatial scales show that trends observed in the abundance of magpie geese in the late dry season on Magela floodplain were highly concordant with similar trends for the same time period across the ARR and the 'Top End' of the NT (fig 2d), the latter area encompassing most of the Australian population. The NT surveys provide 45 years of almost continuous data that suggest cycles of magpie geese numbers over decadal time scales (20–25 year periods, solid trendline in fig 2e). The population dynamics of magpie geese are driven to a large extent by deviations in mean annual local rainfall in river catchments (Bayliss 1989), which itself exhibit similar decadal cycles (see Johnston & Prendergast 1999 for the ARR). The proximate driving variable of magpie geese population dynamics is wetland vegetation (food & nesting material), which is highly correlated to flow, water depth and rainfall. Rainfall and flow are highly correlated, and the dashed curve in figure 2e is the smoothed 'decadal' cycle for mean monthly flow at GS8210009 (009) over 35 years. Time series and CSUM analysis are currently being undertaken for all historical rainfall and flow data in two NT catchments (ARR & Daly River), in order to determine possible relationships between population cycles of other biota (eg other waterbirds, fish, commercial fish catch) and flow as part of the Tropical Rivers Program. Hence, because of the possibility of large-scale 'external' ecological drivers, any meaningful assessment of WH values of waterbirds and other water-dependent 'indicator' species on Kakadu needs to focus on the condition of their seasonal *in situ* habitats and not trends in abundance. This argument may also apply to fish and, possibly, macroinvertebrate communities (see ARRTC16 summary paper by C Humphrey et al).

(a) 1983



(c)



(b) 2003

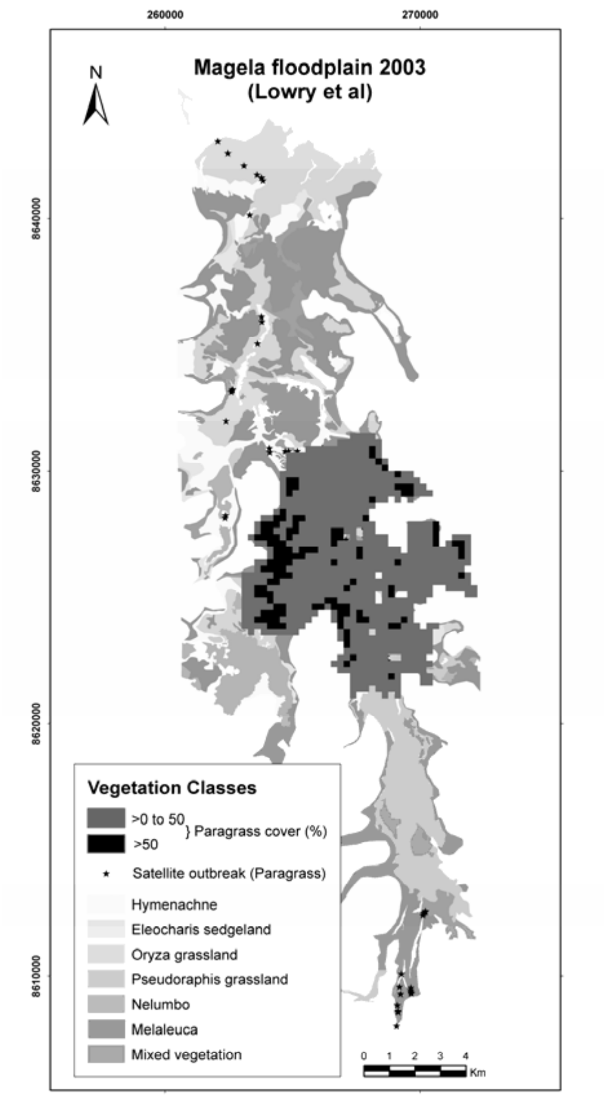


Figure 1 Vegetation change on the Magela floodplain between (a) 1983 and (b) 2003, and the increasing time trend (c) in extent (km^2) of para grass (R^2 = 69%, P<0.04). Legend in (b) also applies to (a).

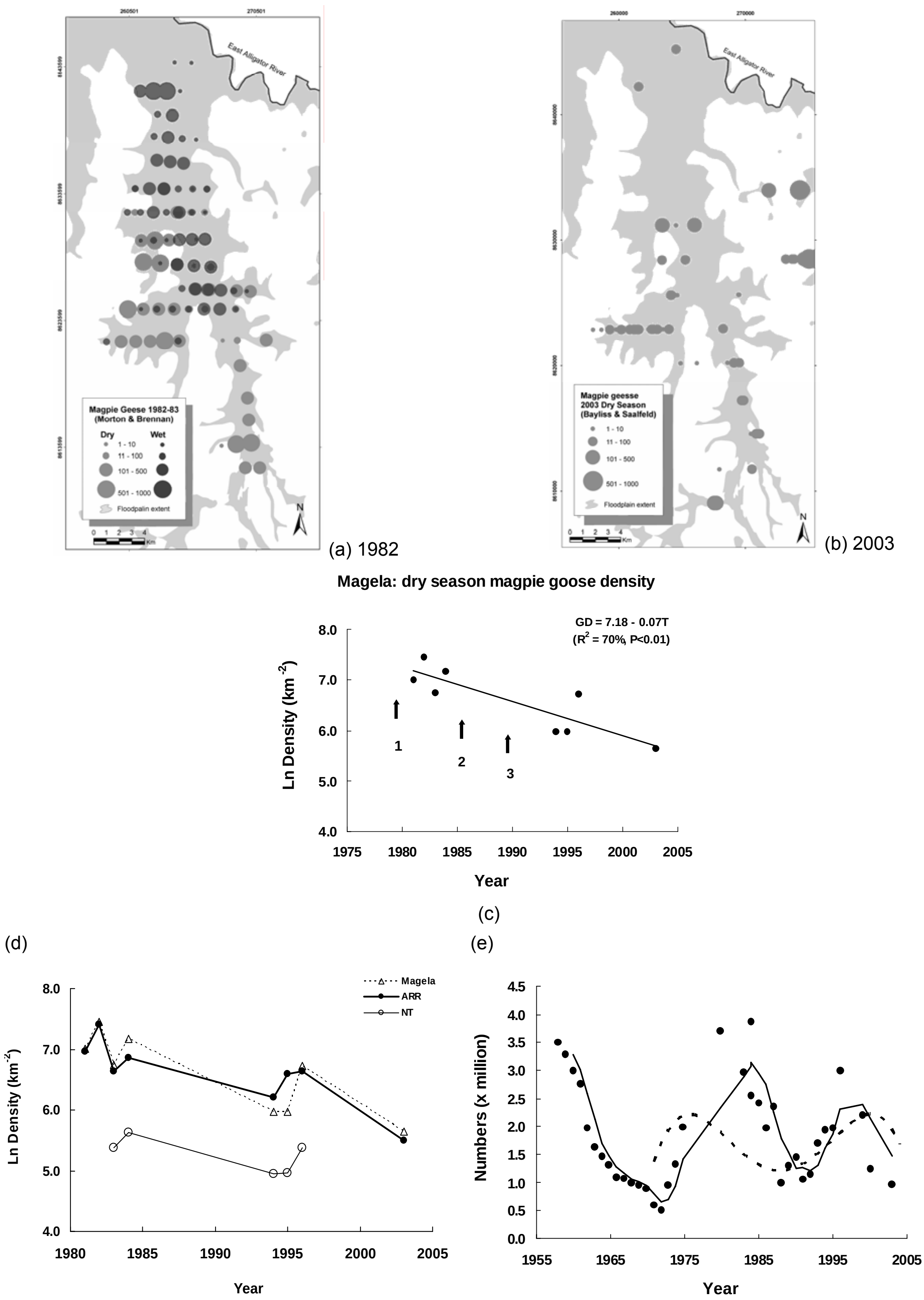


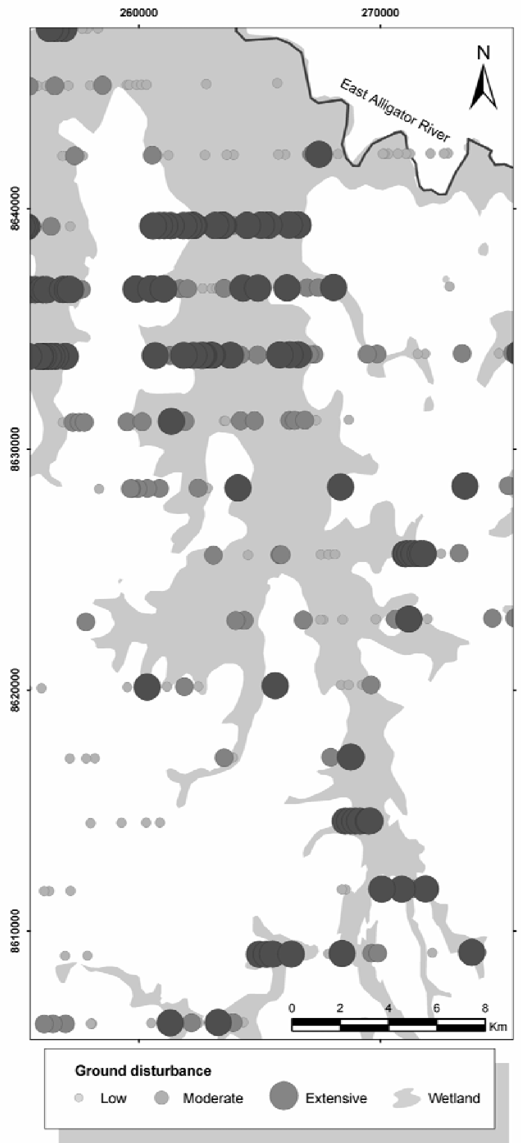
Figure 2a–e Distribution and abundance of magpie geese in the (a) 1982 wet and dry seasons and the (b) 2003 dry season. (c) Declining dry season magpie geese density (Ln km^{-2} floodplain) on Magela (1981–2003; R^2= 70%, P<0.01). Arrows are: 1 – mining; 2 – increase in pig density; 3 – increase in extent of para grass. (d) Concordant trends in dry season density (1981–2003) for the Magela, ARR and the Top End of the NT. (e) Estimated numbers of Magpie Geese in the NT between 1958 and 2003 (solid trendline) and smoothed mean monthly flow at Magela Creek (009) (dashed curve).

Weeds

In the early 1980s para grass had only a small presence on Magela. In the mid 1990s, Knerr (1998) showed that, in the vicinity of the largest infestation, it spread from 132 to 422 ha in five years (1991–1996). This core patch of para grass occupies the centre of the floodplain (fig 1b) and is expanding at 14% p.a. (see regression in fig 1). Put another way, the extent of para grass is doubling every 5 years and, at this rate and in the absence of a strategic control program, the entire floodplain will be lost in 15 to 20 years. However, this time frame may be the 'best case scenario' because satellite patches of para grass have spread along the length of Magela and so that it now occupies about 1250 ha, with new outbreaks occurring in inaccessible dense Melaleuca woodland. The increase in area of para grass between 1991 and 1996 showed a corresponding decrease in area of a community of wild rice, (*Oryza meridionalis*) (Knerr 1998) and Eleocharis sedge (this study). Wild rice and Eleocharis are important food resources for pre-fledging and adult magpie geese, respectively (Bayliss & Yeomans 1990). A Bayesian Habitat Suitability Model (HSM) is being developed with Keith Ferdinands (CDU 2005), and will be used to predict future distribution and potential impacts on native vegetation. This ERA technique has already been successfully applied to the Mary River floodplain (Ferdinands pers. comm.). Additionally, the model will incorporate data from high resolution Quickbird satellite imagery to provide more reliable information on para grass distribution and abundance over different temporal and spatial scales. The methodology developed to date provides a valuable cost-effective monitoring tool for Park managers. Cost-of-control functions have been developed for mimosa (Walden & Bayliss 2004) and now para grass, and are critical for evaluating the benefits and costs of any invasive species management program, which are essentially risk management programs.

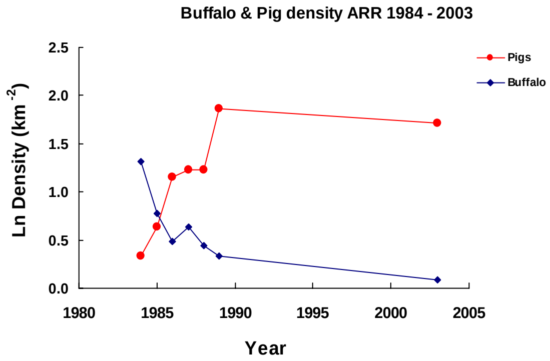
Pigs

This section characterises pig density and damage across floodplains in the ARR and is assumed to be representative of trends on the Magela floodplain. Pig damage was recorded in four damage classes (zero, low, intermediate & high) along aerial survey transects divided into 2 km or 5 km units depending on transect spacing. The frequency of occurrence data were then used to estimate probabilities of damage. No damage was recorded in 1985, corresponding to low pig densities during the early 1980s (Bayliss & Yeomans 1989) when buffalo densities were high. In contrast, extensive pig damage now occurs across the whole of Kakadu, particularly on floodplains such as Magela (fig 3a). These changes corresponded to a rapid increase in pig numbers following sustained commercial harvesting of buffalo in the 1970s followed by the BTEC between 1985 and 1989. During this period pig densities increased at a rate close to their maximum rate of population increase (27% pa, fig 3 top left graph). There is a highly significant negative correlation between the density of buffalo and pigs since 1983 (fig 3, top right graph). In 1989 Kakadu commenced a pig control program in the northern section of the Park, reducing numbers to about 20% by 2003, however, most likely representing 'sustained-yield'. Although ground disturbance damage caused by pigs was only systematically recorded in three of a dozen aerial surveys across the ARR since 1985, damage and density are nevertheless correlated (fig 3 bottom graph). Control cost functions have been developed for pigs in Kakadu (Bayliss & Walden 2003), and a spatially explicit population dynamics model. Pig control data provided by Park managers were used to validate estimates of absolute density.



(a) 2003

(b)



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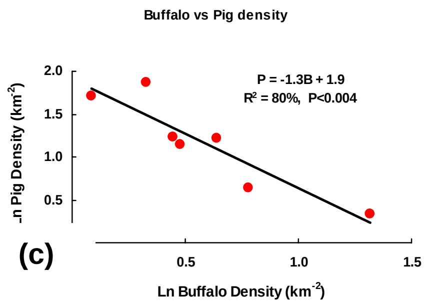
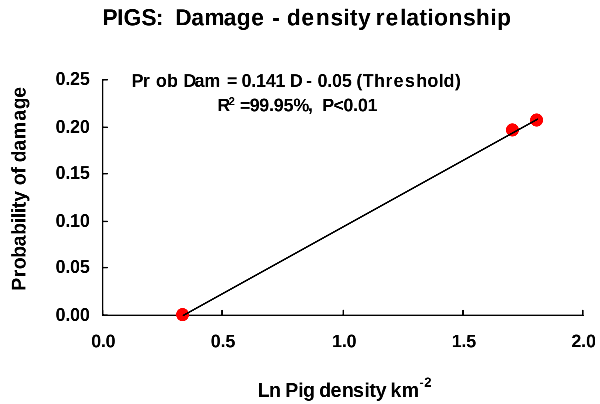




(d)

Figure 3a–d (a) Distribution and intensity (low, medium & high) of ground disturbance damage caused by feral pigs on Magela floodplain (Nov 2003). (b) trends in buffalo and pig density between 1985–2003 in the ARR (top left graph); (c) The inverse relationship between the density of buffalo and pigs in the ARR (top right graph). (d) The threshold relationship between pig damage and density (probability of damage vs Ln (density + 1)).

Fire

The NT Bushfires Council (A Edwards & J Russell-Smith pers comm) provided 25 years of Landsat based fire-scar maps for the NT (1980–2004), which were used to estimate fire occurrence on the Magela floodplain and surrounding Eucalypt woodland. Shape-files were rasterised to a grid of 250 m by 250 m cells. The frequency of fire over 25 years in each cell was converted to probabilities for risk assessment. Although we lack knowledge of the nature of floodplain fires over that period, we resort to expert opinion reflected in the overall Park management goal of obtaining fire frequencies not less that 1 in 4 years. Hence, if the risk of fire in any given location on the floodplain was greater than 0.25, we classified it as a threat to biodiversity values because of the potential to depress the abundance of fire sensitive plant species. However, little is known about the impacts of dry season fires (frequency, intensity, duration) on the structure and composition of wetland vegetation on Magela. Nevertheless, results from the Boggy Plain fire study show clearly that the diversity of wetland plant species increased with Traditional burns if vegetation composition was dominated by monocultures of grasses, such as Hymenachne, and particularly if time since last burnt was greater than 5 years. Therefore, in our ERA for fire we incorporated uncertainty by setting the effects probability at 0.50 (ie hedging bets either way). The floodplain and surrounding woodland have markedly different fire risk profiles (see histograms in fig 4). Floodplain fire occurs on average once every 5 years (mean P=0.20, median =0.125) and, in contrast, the surrounding Eucalypt woodland burns on average once every two years (mean P=0.52, median 0.53). A comparison of the shapes of their PDFs show clearly that fire risk is greater in the woodland because it is more uniformly spread across the entire probability range.

Landscape-scale ERA

A Bayesian Network (BN) is being constructed to link groups of similar landscape-scale ecological risks for an overall assessment. Refined Monte Carlo simulation techniques and sensitivity analysis that rank negative and positive contributions of all inputs are used (Burgman 2005, @Risk software 2002). The end product is a probability density function (pdf) that characterises all landscape-scale ecological risks in combination which can be compared to a similar quantitative risk profile for potential mine-related impacts (see below). The BN approach enables integration of the subjective domain knowledge of experts with risks that can be quantified objectively, hence making all uncertainties transparent as best as possible (Nadkarni & Shenoy 2004). To enhance this process, influence diagrams and decision trees will eventually be used. In the interim, preliminary results for landscape-scale risks that can be quantified and which rely less on expert opinion are reported below (ie climate change and infrastructure risks are temporarily ignored). These are: (i) weeds (para grass, mimosa & salvinia), (ii) feral pigs and (iii) fire. The analytical steps were:

a. for each risk group derive a pdf for exposure probabilities (P_{exp}) based on spatially derived frequency data in each 250m cell across the floodplain. Only para grass and salvinia will be assessed here as mimosa exposure is < 1%;

b. similarly, derive a pdf for effects probabilities (P_{eff}) of each risk group based on expert knowledge, the literature, experiment, frequency and/or empirical data. If completely unknown set the uncertainty level to 0.50. For this report all effects probabilities besides fire (set to 0.50) are arbitrarily set to 1.0. Hence, comparison of risk will be weighted towards exposure.

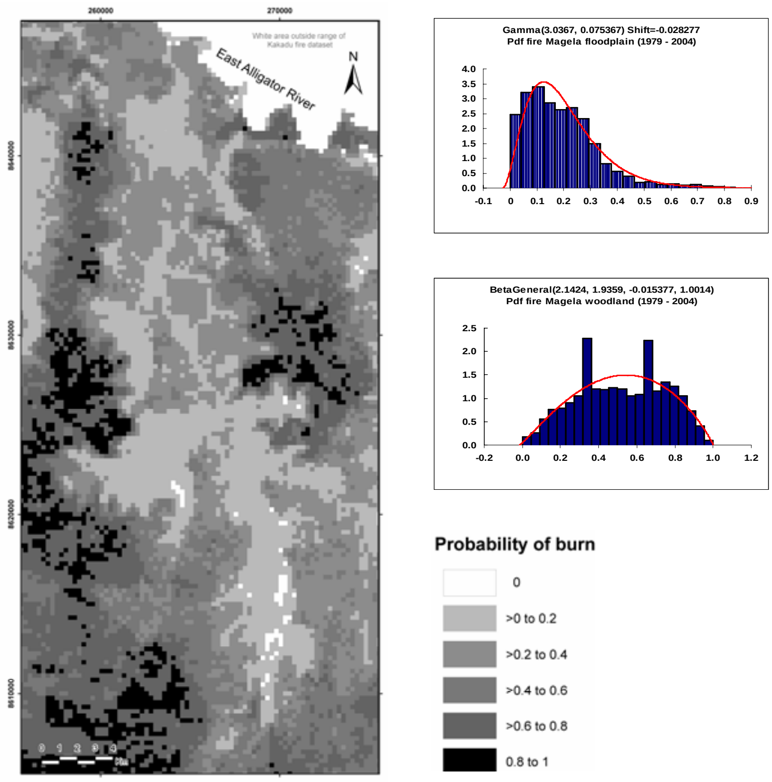


Figure 4 Risk of fire on the Magela floodplain & surrounding woodland (1980–2004). Histograms are probability density functions (pdfs) for frequency of fire occurrence on Magela floodplain (top) and surrounding woodland (bottom).

c. for each group derive ecological risks ($P_{risk} = P_{exp} \times P_{eff}$) from the exposure and effects pdfs above using Monte Carlo simulation (10,000 simulations), essentially characterising the risk profile of each group.

d. combine the risk profiles of all groups using conditional probability theory exemplified below for 3 classes. If P_w = the ER of all weeds combined, P_p = ER pig damage and P_f = ER of frequent unmanaged fires, the combined ER P_c is conditionally derived (using Bayes Theorem) as:

$$P_c = P_w + P_p + P_f - P_wP_p - P_wP_f - P_pP_f + P_wP_pP_f$$

simplified to

$$\{1-[(1-P_w)(1-P_p)(1-P_f)]\}$$

e. use sensitivity analysis to rank the contribution of each risk group to total risk, and ascertain the dependencies between and within groups to total risk.

The details of this process will be reported later, initial results are presented below. Examples of typical pdfs are provided above for the occurrence of fire on the Magela floodplain and surrounding woodland (fig 4). The mean landscape ER is 0.24 (fig 5a), with pig damage ranking first, uncontrolled fire second, and para grass third (fig 5b). Another way of visualising and comparing contributions to overall landscape ER is to overlay individual cumulative probability curves for each (fig 5c).

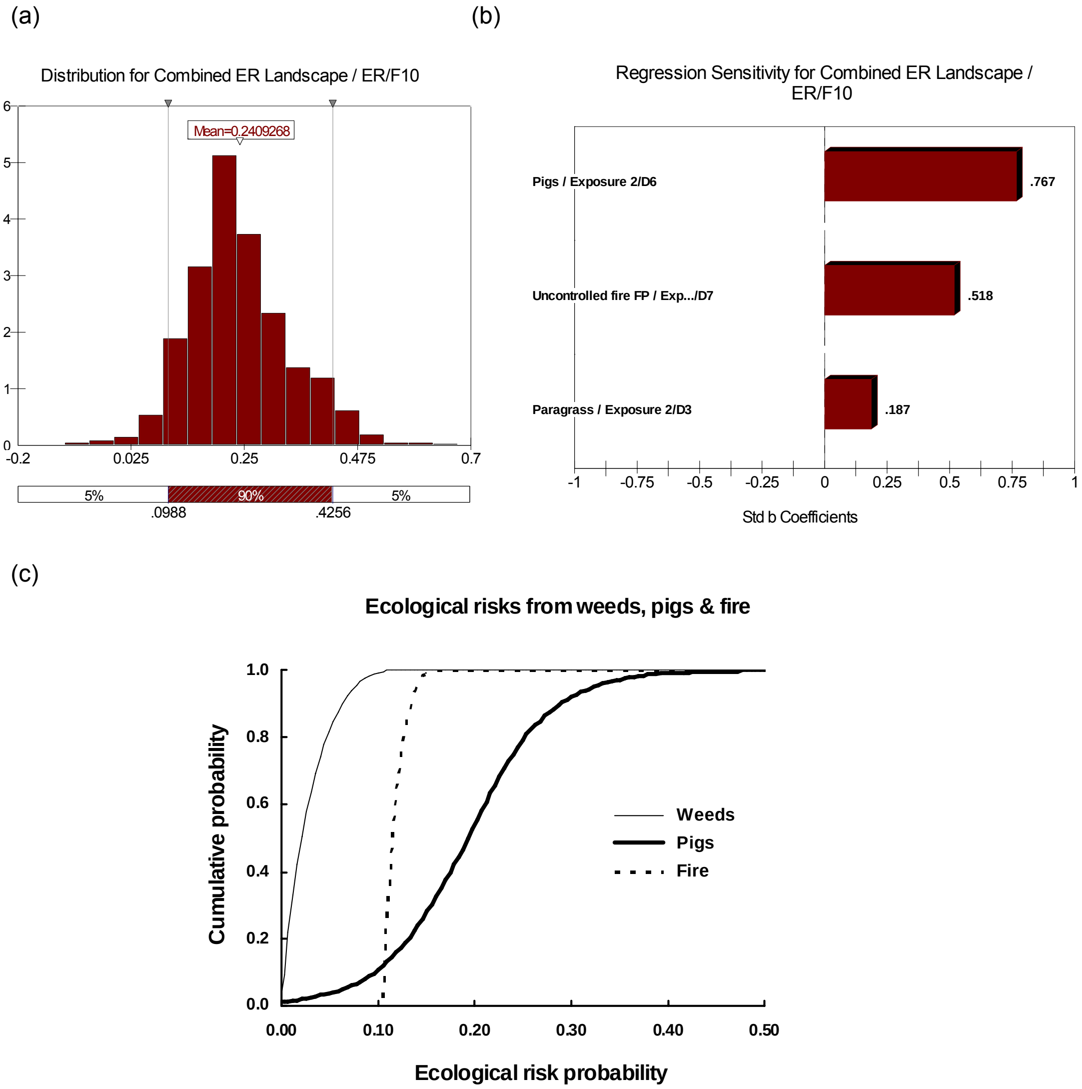
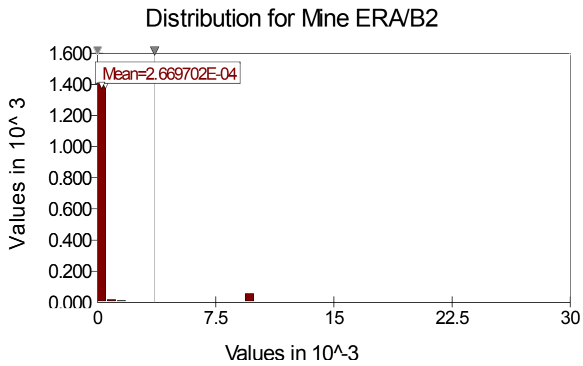


Figure 5a–c. (a) Distribution of combined ecological risks for landscape threats, (b) a Tornado diagram illustrating the relative contributions of each risk group to the combined ERA for landscape threats, and (c) the cumulative probability curves for each landscape ecological risk (para grass, fire & pigs).

Part 2: Ranger – surface water pathway of chemical contaminants

A similar ERA process was adopted for four key chemicals found in diluted effluents discharged from Ranger uranium mine into the surface waters of Magela Creek during the wet seasons between 1998 and 2005. These are uranium (U), magnesium (Mg), sulfate (SO_4) and manganese (Mn). Weekly point sample data at the statutory monitoring site (MG009) were used to characterise off-lease exposure probabilities to aquatic ecosystems downstream of Ranger on Kakadu National Park (Iles 2004). Ecotoxicological end points for U and Mg were used to derive Species Sensitivity Distribution (SSD) models in order to predict the contaminant concentration (Trigger Values, TV) that protect 99% of susceptible aquatic species (van Dam et al 2004a). The models contain a small yet strategic sample across trophic levels and, nevertheless, currently comprise the most robust quantification of ecological effects by any single hazard to date. Although the Mg effects model is complex because Ca ameliorates the toxicity of Mg, use of a 'safe' 9:1 Mg:Ca threshold effects ratio was tractable because van Dam (2005, summary to ARRTC16) developed SSD models for Mg at low background Ca (~ 0.2 mg/L) and with Ca added such that the Mg:Ca ratio was maintained at 9:1. A pdf for Mg:Ca exposure ratios was derived and simulated values that were > or = 9 were combined with the appropriate effects pdf. The TV of 1200 ug/L for Mn recommended by the NWQG (ANZECC & ARMCANZ 2000) is based on ecotox end points so is adopted as an interim value for 99% species protection. A 'low reliability' TV of 15 mg/L for sulfate was adopted based on limited site-specific effects data (van Dam pers. comm.). Best-fit exposure pdfs were: U (Exponential distribution); Mg:Ca ratio (Inverse Gaussian): SO_4 (Log Normal); and Mn (Log Logistic). Best fit effects pdfs were: U (Log Logistic); Mg with no Ca (Exponential); Mg with a Mg:Ca ratio < 9 (Inverse Gaussian). The details of this process will also be reported later, and initial results are presented below. The mean minesite ER of one simulation with 10 000 iterations was 2.7 x 10^{-4}. In contrast to the normal-like distribution of the combined landscape risk profile (fig 5a), the combined pdf for minesite risks is approximately bimodal with 90% of values clustered closed to zero (fig 6a). Note that U exposure and effects had extremely small negative and positive contributions to the combined ER, respectively. Similarly, all other chemicals posed insignificant risks because exposure probabilities never exceeded the 1% species-affected, or other relevant, effects thresholds (fig 6b).

(a)



(b)

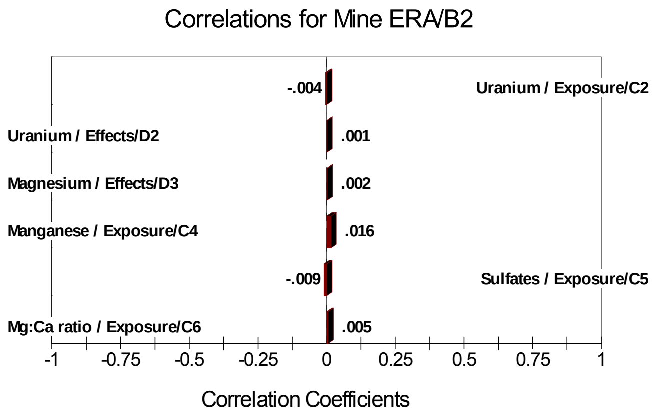


Figure 6 a & b (a) Distribution of combined ecological risks for minesite chemical threats, and (b) a Tornado diagram illustrating the relative contributions of each chemical to the combined ecological risk in the surface water pathway.

Comparison of mining and non-mining ecological risks

Non-mining landscape risks and minesite risks were combined into an overall ERA for Magela floodplain. Results highlight the obvious, in that the significant landscape-scale non-mining risks (fig 7a) effectively swamp the insignificant risks to the surface water pathway posed by chemicals released from the mine (fig 7b). The purpose of the combined simulation was to rank mining and non-mining contributions to overall ecological risk to Magela floodplain to gain clear perspective for risk management recommendations. An appropriate next step would be to compare management investments for both classes of risk given their relative rankings. Future ERA work will: (i) incorporate the above statistical models into influence diagrams and decision trees, in order to explicitly identify all uncertainties; (ii) model different scenarios (eg use of focus and action levels for water quality management cf trigger levels, and model risks from effluents cf with single chemical constituents, see van Dam et al. 2004b); (iii) introduce relevant expert opinion and develop methods to weight varying degrees of belief; (iv) examine other pathways in the conceptual contaminants pathway model; (v) combine ERA models with ecosystem process models (see Guisan & Zimmermann 2000, Lamon & Stow 2004) to examine risks over different time frames and under different management scenarios; and (vi) communicate results to stakeholders.

(a) (b)

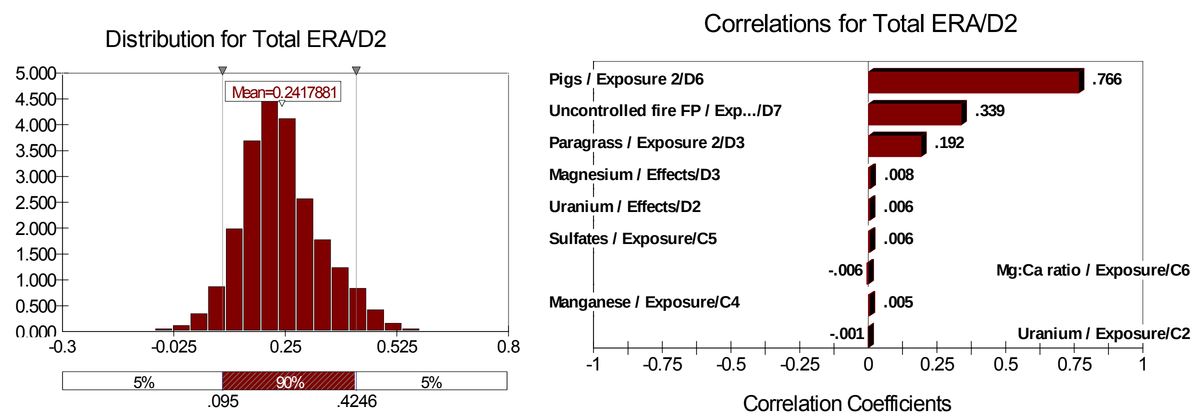


Figure 7 a & b (a) Distribution of combined ecological risks for minesite and non-minesite threats, and (b) a Tornado diagram illustrating the relative contributions of each category of risk to the combined ecological risk to Magela floodplain.

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Significant habitats and species in the Alligator Rivers Region

C Humphrey

Background

This project is being conducted in response to a specific recommendation of the IUCN and the World Heritage Committee. Their concern was that there might be endemic species of animals that, while not at risk from direct contaminant pathways associated with any development at Jabiluka, could be affected by indirect secondary pathways.

Surveys have been conducted on the aquatic fauna of seeps and springs in the stone country of KNP, including in the vicinity of Jabiluka, and western Arnhem Land. Particular attention is being paid to the crustacean groups, the isopods (family Amphisopodidae), freshwater crabs (family Sundalphusidae) and prawns and shrimps (families Atyidae and Kakaducarididae) that occur in these habitats. The results obtained in these surveys are being provided to taxonomists to distinguish and describe new species collected from the sites. If species are identified that are only found in the vicinity of Jabiluka, consideration will be given to pathways for potential impact and possible monitoring programs.

In addition, these endemic species may be vulnerable to the invasion of cane toads and their life stages, through either toxicity (direct contact or from consumption) or competition with tadpoles for food and space.

This work is also relevant to other ARRTC Key Knowledge Needs, including:

3.2.1 *Jabiluka: Research required prior to any development*.

5.3.1 *Baseline studies for biological assessment in West Arnhem Land*. Isopod and shrimp material for taxonomic description includes collections from Arnhem Land. Resulting analyses will contribute information towards mining exploration activities in Arnhem Land

5.4.1 *Baseline monitoring program for Koongarra*. Isopod material for taxonomic description includes collections from Koongarra area.

Progress to date

Work to date on this project is confirming that the freshwater macro-crustacean fauna of stone country in KNP and western Arnhem Land comprises a substantial and significant endemic component. The fauna includes an endemic family of shrimps, the Kakaducarididae, comprising two endemic genera (Bruce 1993, Bruce & Short 1993), as well as an endemic genus of phreatoicidean isopod (*Eophreatoicus*) that has exceptional species-level diversity (Dr G Wilson, Australian Museum, pers comm). Most of these macro-crustacean species have very restricted distributions, often limited to single streams, seeps or springs. This diversity and endemism is believed to be a consequence of the antiquity and persistence of the plateau/escarpment and associated perennial streams, springs and seeps, and isolating mechanisms including fragmentation of habitat (long-term climate changes, erosion) and the generally poor dispersal characteristics of these crustacean groups (Humphrey 1999).

In 2004–05, the following tasks were undertaken:

1 Sampling of critical sites around Jabiluka was completed, leading to closure of KKN 3.2.1. Isopod material was provided to specialists for taxonomic determination (see item 2).

2 The Australian Museum and ***eriss*** have received a research grant from ABRS, to describe isopods of KNP and western Arnhem Land (genus *Eophreatoicus*). To enhance this study and molecular genetics work, a collection of the type material from the King River, in Arnhem Land, was conducted. This trip also contributed to KKN 5.3.1. The formal descriptions of this species flock will adopt local cultural place names in the scientific nomenclature.

3 Small consultancies were established with Prof Jane Hughes (Griffith University) and Dr John Short (BioAccess Australia) to determine the molecular genetics and morphological differentiation of kakaducaridid shrimps.

The molecular genetics work referred to in 2 and 3 above is progressing. The results are confirming the exceptional species-level diversity and restricted distributions of these groups. Even populations of the same (shrimp) species found in various ARR streams are genetically very isolated, which has profound implications for the conservation values of the sites and resident faunas.

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Radiological case study: South Alligator River

B Ryan, P Martin[1], A Bollhöfer & K Pfitzner

Introduction

After seasonal road works in 1999 along the Gunlom Falls access road, an inspection of the site by an OSS employee discovered that the road machinery had exposed tailings directly opposite the old South Alligator Mill tailings dam area. This finding initiated a field gamma survey that was conducted in 1999 followed by an airborne gamma survey that was flown in 2000 (Pfitzner & Martin 2000, Pfitzner et al 2001a,b). Data were evaluated for the Rockhole tailings site and the remaining portion of the South Alligator Valley to quantify the magnitude and extent of radiological contamination in the South Alligator Valley from the mining activities in the 1950s and 1960s and attempt a complete radiological dose assessment of the area (Bollhöfer et al 2002). Results from the study have recently also been published in the *Position* magazine for remote sensing (Pfitzner 2005) as an example of how technology can make a difference to communicating radiological risk.

As the diet of local Aboriginal people of the region is made up of both traditional and shop bought foods (Ryan et al 2005) the ingestion of radionuclides in traditional food items from the area can contribute significantly to the radiological risk. Due to the high concentration factor for ^{226}Ra in freshwater mussels (Johnston et al 1987) the contribution to radiological dose from the ingestion of mussels needed to be determined.

Methods

As part of the radiological investigation and dose assessment studies, samples of freshwater mussels, *Velesunio angasi*, were collected in November 2000 from the South Alligator River (SAR), near and at the confluence of Rock Hole Mine Creek (RMC), and adjacent to the exposed tailings (Ryan et al 2005). Collection sites for mussels, sediments and water were selected following consultations with Parks Australia North (PAN) staff and local Aboriginal people. Radionuclide activity concentrations and activity ratios were determined by alpha and gamma spectrometry. Concentrations of a number of elements (including heavy metals) and stable lead isotopes were determined by ICP-MS. The complete set of results is now available and published (Ryan et al 2005).

The old South Alligator Mill tailings area may be a source of radionuclides and heavy metals washing into SAR in the wet season, and RMC is known to be polluted by acid rock drainage emanating from an old mine adit associated with the abandoned workings of the Rockhole Minesite. In total, 177 mussels, 4 water and 6 sediment samples were jointly collected by ***eriss***, PAN and Aboriginal Traditional Owners from sites either potentially exposed (downstream) or unexposed (upstream) to mine waste contaminants.

The age of each mussel was determined by placing the shell over an incandescent light source and counting the (annual) dark bands (annuli). The dried and ground flesh of the mussels were combined according to age class and site, and a composite sample of each age class was cast in

[1] Formerly SSD; now Agency's Laboratories Seibersdorf, IAEA, A-1400, Vienna, Austria.

epoxy resin for determination of radioisotopes of lead (^{210}Pb), thorium (^{228}Th) and radium (^{226}Ra & ^{228}Ra) by gamma spectrometry. Mussels ≤ 1 year of age, or an age class with insufficient mass for analysis by gamma spectrometry, were analysed by alpha spectrometry.

A sub-sample of dried and ground composite material of each age group from each site was analysed by ICP-MS for aluminium (Al), arsenic (As), barium (Ba), cadmium (Cd), calcium (Ca), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), manganese (Mn), nickel (Ni), potassium (K), rubidium (Rb), selenium (Se), sodium (Na), strontium (Sr), uranium (U) and zinc (Zn). Sub-samples of a range of age class composites from each site were analysed for stable lead isotopes with ICP-MS.

Figure 1 A freshwater mussel, *Velesunio angasi*, from the South Alligator River.
Counting of the distinctive dark bands (annuli) is used to determine the age of the mussels.

Results

The radionuclide and metal concentration measurements indicate that downstream RMC and the tailings area some contamination, although relatively small, has occurred. In particular the ^{226}Ra/^{228}Ra activity ratios in the mussel flesh indicated that mussels from the potentially exposed sites have accumulated relatively more ^{226}Ra compared to mussels of the same ages from sites upstream of RMC and the tailings area.

Using the age, weight and proportional information gleaned from our study and a hypothetical collection of freshwater mussels by local Aboriginal people we estimated the committed effective dose for a 10-year-old child from the ingestion of freshwater mussels. The resulting total committed effective dose of 0.08 mSv, assuming the child ate 2 kg of mussels in a year, is based upon average activity concentrations of ^{226}Ra and ^{210}Pb from all sites and age groups in the collected samples from the upper South Alligator River. This estimate is somewhat lower than an earlier estimate given in Bollhöfer et al (2002) and also includes the dose originating from radionuclides accumulating naturally in the mussels.

The corresponding doses arising from ^{238}U intake are extremely low because the uranium concentration factor, and thus the uranium concentration in mussel flesh, and the dose conversion factor are much lower. For example, assuming a 10-year old child eating 2 kg (wet weight) of flesh from mussels from where the tailings enter the South Alligator River, the committed effective dose from the intake of uranium would only be 0.0001 mSv. For comparison, the dose limit for a member of the public that applies to a practice (such as an operating uranium mine) is 1 mSv per year additional dose to the natural background.

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Research consultancies

This section contains a summary of non-uranium mining related external projects carried out by ***eriss*** during 2004–05. Commercial-in-confidence projects have been excluded from this compilation.

Australia's tropical rivers – an integrated data assessment and analysis

R van Dam

A preliminary ecological risk assessment of the impact of Ginger ants (*Solenopsis geminata*) on colonies of seabirds at Ashmore Reef

P Bayliss

Climate change vulnerability of wetlands

I Eliot, MJ Saynor, K Pfitzner & M Eliot

Australia's tropical rivers – an integrated data assessment and analysis

R van Dam[1]

Introduction

Australia's tropical rivers – an integrated data assessment and analysis, is more commonly known as the *Tropical rivers inventory and assessment project* (TRIAP). The TRIAP, funded by Land & Water Australia and the Natural Heritage Trust 2 is a collaborative effort between ***eriss***, James Cook University and the University of Western Australia, with additional involvement of the University of Wageningen in the Netherlands. It is currently the key research activity of the National Centre for Tropical Wetland Research (***nctwr***). The project aims to provide an information base to support the management of Australia's tropical rivers and consists of three sub-projects: (i) mapping and inventory; (ii) risk assessment of key threats; and (iii) development of a framework for evaluating ecosystem services. The project focus during 2004-05 was on sub-projects 1 and 3. A stakeholder workshop was held in November 2004 and attracted representatives from government, indigenous and research interests. Nineteen presentations were delivered, providing stakeholders with a summary and progress update of the TRIAP, and seeking open discussion. Details of project activities and progress during 2004–05 are provided in the Project Milestone Reports available from the TRIAP web site (www.nctwr.org.au/publications/tropical-rivers-reports.html).

[1] Project team includes the following SSD staff and external personnel: SSD – Renée Bartolo, Peter Bayliss, James Boyden, Gary Fox, Chris Humphrey, David Jones, John Lowry, Dene Moliere, Suthidha Nou, Mike Saynor, Dave Walden; JCU – Mirjam Alewijnse, Damien Burrows, Barry Butler, John Dowe, George Lukacs; UWA – Ian Eliot, Matt Eliot; University of Wageninen – Dolf de Groot, Sophie Bachet, Clement Mabire, Pujan Shrestha, Bas Verschuuren, Olga Ypma, Matt Zylstra; International Water Management Institute – Max Finlayson, Maria Bellio; CSIRO – Emma Woodward.

A preliminary ecological risk assessment of the impact of Ginger ants (*Solenopsis geminata*) on colonies of seabirds at Ashmore Reef

P Bayliss

Ashmore Reef Nature Reserve is located within Australian waters off the coast of northern Western Australia, and covers an area of about 583 km^2. The islands in the reserve provide important nesting sites for colonial seabirds and turtles, and its marine and terrestrial ecosystems are recognised by a host of international conventions and agreements, in particular the Ramsar Convention. The aims of this project were: (i) to gain a better understanding of the potential ecological risks of the introduced Ginger ant (*Solenopsis geminata*) to the seabird colonies of Ashmore Reef; and, if necessary, (ii) to recommend risk management action to DEH. The project was managed by Maria Bellio, who has since left ***eriss***, with support from other staff. A field trip was undertaken in November 2004 to collect quantitative data on the distribution and abundance of Ginger ants in relation to the nesting success and chick mortality seabird species breeding at the time, such as the Common noddy. A comprehensive desk top risk assessment was then undertaken using previous published knowledge and the field results. Field results and the associated risk assessment show specifically that Ginger ants are currently a serious threat to the recruitment of Common noddies at Ashmore and, hence, by implication to other seabird species. The risks to seabirds in general could even be greater because Ginger ant populations have the potential to erupt to very high levels, thereby substantially increasing current high natural and ant-induced mortality rates and, of all seabirds that nest on Ashmore, the Common noddy is probably one of the least susceptible species to Ginger ants. The field results, risk assessment and recommendations for a measured management response have been drafted into an SSR that has been externally reviewed. Revision is underway with completion time May/June 2006.

Climate change vulnerability of wetlands

I Eliot[1], MJ Saynor, K Pfitzner & M Eliot[2]

The Australian Greenhouse Office (AGO) of the Commonwealth Department of the Environment and Heritage engaged ***eriss*** to assess and develop tools for assessing the vulnerability to climate change of coastal wetlands and rivers in the Gulf of Carpentaria Region. The project had two parts: (1) description of protocols, frameworks and tools appropriate for assessing the vulnerability to climate change of coastal wetlands and rivers in the Gulf of Carpentaria Region; and (2) determination of the sufficiency of existing data sources as well as identification of any gaps in priority data and information required for undertaking a vulnerability assessment in the Gulf of Carpentaria Region.

With respect to Part (1), the Ramsar Wetland Convention and Asian Wetland Inventory protocols for wetland inventory were considered most applicable to the region. The recommended framework conforms to the recommended protocols and is based on methodologies applied to wetlands in the wet-dry tropics. A data acquisition program for vulnerability analysis of coastal wetlands in the Region was devised and recommended. Framework application tools include: spatial information management; measurement and modelling of environmental change; risk assessment; statutory and administrative instruments; and determination and implementation of adaptive management procedures. Adoption of the recent National Committee of Coastal and Ocean Engineers guidelines for data acquisition, collation and management is recommended. Their guidelines support rigorous standards for numerical modelling and forecasting requirements and stress that long-term strategic data collection programs are fundamental to issues related to climate change and sea level rise.

With respect to Part (2), a considerable volume of information is available for broad-scale strategic planning for sea level rise, including recent releases of maps and information by the AGO. Preliminary analyses of selected examples of the available information demonstrated that it is feasible to undertake vulnerability and adaptation assessments however, stakeholder involvement was not addressed. Current climate change and sea-level rise projections for the region were the basis for using the tools and data sources identified for the preliminary analyses. On the basis of this conclusion it was recommended that the AGO resource ***eriss*** to undertake a vulnerability and adaptation assessment for the Gulf of Carpentaria Region as a demonstration project.

[1] School of Earth and Geographical Sciences, Faculty of Natural and Agricultural Sciences, The University of Western Australia, Mail Drop M004, 35 Stirling Highway, Crawley, Western Australia 6009.

[2] School of Environmental Systems Engineering, Faculty Engineering, The University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009.

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Appendix 2 ARRTC Key Knowledge Needs 2004–2005

Overall objective

To undertake relevant research that will generate knowledge leading to improved management and protection of the ARR 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.

Background

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.
- 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:

4 maintain the attributes for which Kakadu National Park was inscribed on the World Heritage list;

5 maintain the ecosystem health of the wetlands listed under the Ramsar Convention on Wetlands (ie the wetlands within Stages I and II of Kakadu National Park);

6 protect the health of Aboriginals and other members of the regional community; and

7 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:

8 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;

9 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;

10 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
- Knowledge management and communication.

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

KKN 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.

KKN 1.1.2 Atmospheric transport of radionuclides

Using existing data and atmospheric transport models, review and summarise, within a risk framework, dose rates for members of the general public arising from operations at the Ranger mine.

1.2 Ongoing operational issues

KKN 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 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 (ie biomagnification) of uranium and other Ranger mining-related contaminants from all exposure pathways and including the identification of key information gaps.

KKN 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.

KKN 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.

KKN 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.

KKN 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.

KKN 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 (activity Median Aerodynamic Diameter) and solubility of ore and product dusts in a range of exposure scenarios.

1.3 Monitoring

KKN 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

KKN 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.

KKN 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.

KKN 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.

KKN 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.

KKN 2.1.5 Geomorphic behaviour and evolution of the landscape

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 mine site with respect to the erosional effects of extreme events.

KKN 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 assessed so that estimates can be made of the likely change in exposure rates compared to pre-mining conditions.

KKN 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.

KKN 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

KKN 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.

KKN 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.

KKN 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 exclusion of weeds and the effects of fire, hydrology and erosion on the rehabilitation strategy.

KKN 2.2.4 Radiation exposure pathways associated with ecosystem re-establishment

Bioaccumulation studies conducted to date have focused 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

KKN 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.

KKN 2.3.2 Geochemical characterisation 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.

KKN 2.3.3 Aquifer characterisation and whole-of-site model

The aquifers surrounding the tailings repositories (Pits 1 & 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.

KKN 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

KKN 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 treatment technologies and enhanced evaporation technologies that can be implemented for very high salinity process water.

KKN 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.

KKN 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.

KKN 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

KKN 3.1.1 Monitoring during the care and 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

KKN 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

KKN 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.

KKN 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

KKN 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 ALLIGATOR RIVERS REGION

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.

KKN 5.1.1 Re-assess and prioritise the landscape program

A review is required, within a modelling conceptual 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.

KKN 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

Mining 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 mining exploration sites in the ARR.

KKN 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.

KKN 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.

KKN 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 Alligator Rivers Region 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 the following.

6.1 Integrated framework

KKN 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 where the scientific information is relevant, and how it informs on the various risks to the system and its people from the uranium mines.

6.2 Uncertainty analysis

KKN 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 high risk areas where the uncertainty is great 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

KKN 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

KKN 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.