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The rehabilitation of Nabarlek Uranium Mine

Proceedings of Workshop,

Darwin NT, Australia

18–19 April 2000

Edited by DA Klessa

Environment Australia
Department of the Environment and Heritage

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Preface

The rehabilitation of Nabarlek minesite is a ‘landmark’ in more ways than one. As the first of the modern-day uranium mines in the Top End to go full cycle from cradle to grave, the principles of best practicable technology — an integral part of the strict compliance regime which accompanied the active mining phase — now applies during rehabilitation. By necessity, the process of rehabilitation requires that the concerns and interests of stakeholders, particularly those of the Traditional Owners, are taken fully into account in achieving outcomes. In the case of Nabarlek, land is being returned to bush and the vexed problem of adjudging the point in time at which reinstated vegetation (and at the broader scale, ecosystem function) is deemed to be sustainable and, importantly, meets the required standards must be decided. Having defined these standards in relation to public health, environmental protection, site stability, hunting and gathering needs, and aesthetics, their interpretation in the context of a heterogeneous system prone to change from the perturbations of fire, weeds, feral animals and climate can be difficult.

These *proceedings* of the Workshop on the Rehabilitation of Nabarlek attempt to tackle some of these important technical issues. A large part of workshop time was conducted in open forum and a record of these discussions between stakeholders representing government, Traditional Owners and experts in various aspects of rehabilitation is contained in the first part of the *proceedings*. The remainder contains the papers given by invited speakers.

DA Klessa

July 2001

Executive summary

A workshop was called in April 2000 by the Supervising Scientist to examine technical issues associated with the rehabilitation of Nabarlek and was attended by stakeholders representing Federal and Territory Governments and Traditional Owners. Invited experts in revegetation and 'state of the environment reporting' addressed the workshop and chaired sessions. The workshop was conducted as an open forum for discussion and its outcomes have been presented to the Nabarlek Minesite Technical Committee.

The key questions considered by the workshop were as follows:

- Has rehabilitation at Nabarlek reached a stage where the mining company can be discharged of its responsibility?
- If not, has adequate monitoring data been collected that will allow rehabilitation success to be assessed?
- What are the lessons learnt that can be applied now, or for further research which will help in achieving rehabilitation success?

In answering these key questions a number of recommendations were made by the delegates. Those receiving consensus support are listed below:

Revegetation

1 More information is required to assess revegetation success particularly its dynamics during the early stage of development.

2 Amongst the secondary revegetation criteria which might be used to gauge success are species abundance, recruitment, competition, inflorescence, vigour, fire tolerance, weed density and soil C:N ratio.

3 A consultancy report conducted on behalf of the mine company (and the NLC) on progress in revegetation at Nabarlek appears to have omitted data that are important for substantiating the report's conclusions. A request to the consultant for the raw data should be made.

4 At present, the state of revegetation at Nabarlek does not meet the expectation of stakeholders and the following work is required:

   - the surface hydrology of the former ponds area needs to be classified to determine which species to plant. In particular, there is a need to determine if some areas are not amenable to tree species.
   - where appropriate, the ponds area should be enriched with the interplanting of *Melaleuca* tube stock and seed.
   - to assist in the establishment of trees and shrubs, grass should be removed from appropriate land units of the pond area.
   - the former pit area shows successful recruitment but requires further assessment of species patterns and densities.

5 It is recommended that aerial photography be used to delineate upland and run-on zones (which favour *Melaleuca* establishment) and as a tool to assess revegetation success over the whole site.

6 Bush tucker plants should not be planted on site.

7 The scope for including a monitoring program that uses Ecosystem Function Analysis (EFA) techniques to assess revegetation will be examined by the Supervising Scientist.[1]

8 It is recommended that annual assessment of revegetation success by the company's consultant should continue and be supplemented by information gained from other sources including Australian Centre for Mining Environmental Research (ACMER) research.

Monitoring

9 Groundwater monitoring should continue but the sampling program should be designed to not only provide public assurance on environmental protection but also be used to examine the veracity of model predictions for contaminant movement from tailings. To this end, a program to maintain and repair bore hole access should be adopted and, if necessary, new bores sunk.

10 Allied to (9), is the need to review the data requirements for modelling and to provide feedback on monitoring requirements and borehole location needs.

11 Surface water monitoring at Nabarlek should continue.

12 Radiological dose assessment of bush tucker plant consumption and its risk assessment will be conducted by ***eriss***. Data requirements may extend to fish and mussels. Radon emanation monitoring will continue.

13 An assessment of the risk of erosion in the area south of the former waste rock dump will be conducted by ***eriss*** and, if required, recommendations provided on remedial action.

Fire management

14 Preventative fire management is seen as crucial to revegetation success at Nabarlek. To this end, fire should be kept out of the revegetated areas for at least 5 years.

15 Risk assessment of fire damage to the revegetated areas should be conducted at least every two years and should also record plant species, abundance and spatial and age-class distributions to determine the potential for damage and recovery.

16 Grasses should be managed appropriately to reduce fuel and competition with trees and shrubs for resources.

17 Fire breaks should be maintained.

Erosion control

18 The implications of deteriorating road and drain conditions on erosion in the area should be examined. To this end, the advice of the NT Government roads engineer should be sought.

19 The future of local road access to Nabarlek and its upkeep needs to be clarified by stakeholders.

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[1] The Supervising Scientist has since agreed to financially support an ACMER project on Ecosystem Function Analysis (EFA) with field studies at Nabarlek.

20 An assessment of erosion risk from water flowing southward from the former waste rock dump will be conducted by ***eriss***.

21 Remedial treatment to gullies and deep rills parallel to the southern boundary fence is required.

Weed control

22 A survey should be conducted to collate a weed list for Nabarlek which should account for both disturbed and undisturbed areas.

23 A weed control strategy should be developed for problematic weed species:

- as defined under NT legislation, and
- which pose problems (fuel load and competition) to the successful establishment of trees and shrubs on site.

Feral animals

24 The damage currently being sustained on site from feral animals is unknown but it is recommended that the existing fence around the site be repaired and the gates be replaced so that there is a measure of control by exclusion.

Acknowledgments

The editor would like to thank Cliff Lloyd, Meryl Triggs and Alex Zapantis for their assistance. Thanks also go to Gail Barrowcliff for her organisational skills in helping to plan and run the workshop.

Transactions of the workshop

compiled by C Lloyd & DA Klessa

Introduction

The Nabarlek Workshop was held on 18–19 April 2000 at the Mirambeena Tourist Resort, Darwin and hosted by the Office of the Supervising Scientist (***oss***). The catalyst for calling the workshop was the release of a final report[2] (Adams Ecological Consultants 1999) on behalf of Pioneer International Limited which examined revegetation success at Nabarlek since its rehabilitation in 1995/96. Independently, a review of the progress of revegetation at Nabarlek was also conducted by the Supervising Scientist (Prendergast et al 1999) which failed to reach the same conclusions given by the Adams report.

Consequently, the Supervising Scientist concluded that a forum involving stakeholders in the exchange of views and ideas on rehabilitation success at Nabarlek was timely, and should consider the following key questions:

1 Has rehabilitation reached a stage where the mining company can be discharged of its responsibility?

2 If not, has adequate monitoring data been collected that will allow the success of rehabilitation to be measured?

3 What are the lessons learnt that can be applied now, or for further research that should be done?

Around 40 invited delegates attended the workshop representing the Northern Land Council (NLC), the Northern Territory Department of Mines and Energy (NTDME), CSIRO, Earth, Water and Life Sciences (EWL), Department of Industry, Science and Resource (DISR), ***oss*** and ***eriss***. Regretfully, Pioneer International Limited and Adams Ecological Consultants declined their invitations. Specialist input was provided by David Tongway (CSIRO), Clive Bell (ACMER),[3] Dieter Hinz (revegetation consultant) and Jim Derrick (State of the Environment, Department of the Environment and Heritage).

On the day before the start of the workshop, eight delegates from the NLC and DISR and ***oss***, invited specialists David Tongway, Clive Bell and Dieter Hinz, and two Traditional Owners, spent three hours at Nabarlek walking the site after a briefing session at ***eriss***. The objective of the visit was to help familiarise the specialists with the site so that they were able to view its characteristics at first hand. Feedback from the specialists attending the visit indicated that the information they had gleaned from it was useful when they later considered revegetation issues at the workshop.

The workshop program is given in an annex to the transactions of the workshop. This is followed by the workshop papers delivered by the speakers:

- PW Waggitt — *The decommissioning and rehabilitation of the Nabarlek uranium mine, northern Australia*

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2 Henceforth referred to as 'the Adams report' (unpublished report).

3 Australian Centre for Mining Environmental Research

- B Lewis — *Nabarlek Traditional Owners' perspective on the current state of revegetation*
- RA McGill & RE Fox — *Nabarlek rehabilitation: The Supervising Authority's perspective*
- A Zapantis — *Nabarlek rehabilitation: The Supervising Scientist's perspective*
- PW Waggitt — *Nabarlek minesite rehabilitation: The Commonwealth's expectations*
- KG Evans, MJ Saynor & GR Hancock — *Rehabilitation at Nabarlek: Erosion assessment 1999*
- P Martin, S Tims & B Ryan — *Rehabilitation at Nabarlek: Radiological issues*
- G Parker — *Nabarlek: Chemistry issues*
- D Tongway — *Monitoring indicators of minesite rehabilitation success*
- DA Hinz — *Termites as ecological indicators of mine-land rehabilitation in tropical Australia*
- J Derrick — *State of the Environment reporting: Links with minesite rehabilitation.*

Day One

1 Welcome and introduction (A Johnston, Supervising Scientist)

The Supervising Scientist welcomed delegates, thanked the organisers of the workshop and stated the objectives of the workshop (see above). He stressed the significance of Nabarlek as the first modern uranium mine in Australia to be rehabilitated and drew comparisons with the problematic history of the rehabilitation of the abandoned mines of the South Alligator Valley and Rum Jungle. Compared with these older mines, the expectations for the rehabilitation of Nabarlek by both Government and Traditional Owners were more rigorous and to a much higher standard.

It was timely that the workshop had been called to examine the success of rehabilitation at Nabarlek. The Supervising Scientist reminded delegates of the background to the appointment of an independent consultant to assess rehabilitation success. This appointment stemmed from an agreement between the NLC and the mining company with the remit of the expert to decide whether the agreed revegetation standards or criteria had been met. In this regard, the Supervising Scientist noted that the Commonwealth was not a party to the agreement and hence was not bound by it. Nevertheless, the Supervising Scientist has responsibilities under the *Environment Protection (Alligator Rivers Region) Act 1978* to promote and assist in devising and developing measures for the protection and restoration of the environment of the Alligator Rivers Region (ARR) from the effects of uranium mining and in advising the Minister of these matters.

It was appropriate that the Minesite Technical Committee (MTC) should consider the outcomes of the workshop contained in this report and determine their implementation. Also the MTC would provide guidance on the publication of this report in full or in part. He regretted that neither the mining company nor the consultant had chosen to attend, but the Supervising Scientist stated that this should not detract from the conclusions the workshop reached. Finally, the Supervising Scientist reminded delegates that although revegetation was the main focus, it was the technical issues associated with the rehabilitation of Nabarlek that he wished the workshop to consider.

2 History and background to Nabarlek (Chair: A Zapantis, *oss*)

Papers delivered in this session:

Mining PW Waggitt (*oss*)

Rehabilitation PW Waggitt (*oss*)

Note that aspects of the above two papers are contained in Waggitt PW — *The decommissioning and rehabilitation of the Nabarlek uranium mine, northern Australia* (Workshop papers, pp16–25, this volume) which is taken from Waggitt (1998).

2.1 Discussion

Topography and drainage in the former pond area was discussed with reference to:

- the presence of poorly drained areas (to the north and north-east);
- the relationship of the landscaped surface to its former topography.

An opinion was expressed that better grade control on the pond area would have improved drainage, and tree and shrub growth in what had now developed into wet patches. It was noted that deep ripping over the whole pond area had preceded seeding which would have assisted drainage and increased the rainfall intensity threshold for surface runoff.

The question of the type of fill used, as a possible factor influencing site drainage over the ponds area, was raised. In this regard, it was noted that the topsoil, which had been stockpiled, had harboured weed seeds within the surface 15 cm depth. Consequently, it had been recommended to the company by ***eriss*** prior to rehabilitation that this portion of the topsoil stockpile be buried. However, the details of the fill-in of the former ponds were not known or whether the current drainage problems in the area had been influenced by the materials used.

The question as to whether the final landform over the ponds area was contoured by taking account of the original landform was raised. Based upon available records, this did not appear to be the case. It was noted that aerial photographic records, which pre-dated mining development at Nabarlek, are probably available and would provide a useful baseline of pre-existing conditions including vegetation of the area. It was known, however, from engineering soil surveys of the ponds area that wet patches were present (re buffalo wallows on soils derived from the dolerite outcrop) and that given the swampy area to the north which is the source of Buffalo Creek that a high groundwater table was present naturally.

The background to the revegetation agreement between the company and the NLC was raised by the NLC. The NLC stated that they accept Adams Ecological Consultants as final arbiter, but nonetheless the NLC felt there was a degree of corporate amnesia. While a draft agreement dated June 1996 was responded to by a letter from the NLC to QML in which changes were suggested, including how the consultancy would be carried out, the NLC has no copy of a signed agreement. Consequently, according to the NLC, the 1993 settlement deed takes precedence as the principal document which has detailed secondary criteria for the assessment of rehabilitation success. Thus, it is the NLC's contention that these specified secondary criteria should have been taken into account by Adams Ecological Consultants.

3 Perspectives on desired outcomes for rehabilitation at Nabarlek (Chair: A Johnston, Supervising Scientist)

Papers delivered in this session:

Nabarlek Traditional Owners' perspective on the current state of revegetation — B Lewis

Nabarlek rehabilitation: The Supervising Authority's perspective — RA McGill & RE Fox

Nabarlek rehabilitation: The Supervising Scientist's perspective — A Zapantis

3.1 Discussion

On a question about the local people, it was noted that over the history of the mine and its rehabilitation there had been limited involvement of the Traditional Owners. Traditional Owners had been involved with seed collection in the 1980s but this had not included employment.

Traditional Owners, irrespective of age, shared similar perceptions and attitudes towards Nabarlek. The Traditional Owners wanted to know what was achievable in revegetation, to be able to discuss alternatives with the company and to be more involved. The feeling was that the company was accelerating close-out but it was unclear from the community whether there was any perception of the time that might be needed to rehabilitate. The view of the NLC was that with only three years having elapsed for revegetation, this was insufficient to determine whether the expected plant community successions were in place (in accordance with secondary standards). There had been discussion with the mine company about including and enhancing bush-tucker species in seed mix. However, given concerns with planting over the tailings repository (ie pit), bush tucker species were to have been confined to the radiological uncontaminated areas (ie the waste rock dump and pond areas).

The suggestion was made from the floor that in principle the time the NTDME should withhold a rehabilitation certificate should be a minimum of 10 years. In response the NTDME stated that in some situations this could impose a significant financial burden on companies through rents and bonds.

The general comment was made from the floor that standard criteria should be set by Government for future rehabilitation works at mines. Since the workshop was dealing specifically with Nabarlek, the legislative context of revegetation at Nabarlek was more fully explained. Agreement under the *Aboriginal and Land Rights (Northern Territory) Act* means that while Government might approve the operation, the legislative framework requires the company to reach an agreement with the NLC. Throughout this process, the NTDME and the Commonwealth are not privy to what the Company and the NLC might agree, which adds an additional element of complexity.

The relationship between the NTDME and Supervising Scientist to mining and revegetation issues in the ARR was questioned. The NTDME responded by stressing the usefulness of the formal working relationship that exists between the two, whereby the Supervising Scientist can provide advice on revegetation and landscape issues particularly for uranium mines. In this regard, the NTDME tries to gain expertise from wherever it can.

In answer to a question, the Supervising Scientist indicated that to his knowledge the basis of the agreement between the NLC and the company was one in which no specific revegetation criteria or targets had been set, rather a set of secondary standards. In this regard, the NTDME as the Supervising Authority would be required to make a judgement at some point in time as to whether the secondary standards had been achieved. It was the Supervising Scientist's contention that the best outcome would be one which was reached by the NTDME taking full consideration of the views of all other stakeholders.

It was the Supervising Scientist's view that the gap which had appeared between the views and wishes of the Traditional Owners and those of the mining company had to be bridged. The concerns of the Traditional Owners had to be addressed but in doing so the clock could not be simply turned back. In response, the NTDME agreed that a decision on close-out would have to be made in the absence of specific revegetation criteria which meant that a consensus would have to be reached.

The Supervising Scientist further reiterated that details of agreements between the mining company and the Traditional Owners should be made known to Government so that the expectations for environmental protection are known and that the set standards and criteria are specified in a satisfactory way. It was unfortunate that for Nabarlek this had not been the case.

The NTDME recognises that close-out criteria need to be customised for each mine site and end use, but that specific as opposed to generic criteria are difficult to set. In addition, the issue is further complicated by on-going developments in world best-practice standards. Consequently, these points alone in conjunction with changing personnel in stakeholder groups stress the need for agreement to be reached well in advance of mine closure. Also changes in staff within stakeholder groups demand that careful attention be paid to good record keeping and communication in the negotiation and meeting of agreements. The view was expressed from the floor that closure criteria can only be decided when a mine comes up for rehabilitation. Only guidelines can be established from the start. Consequently, there needs to be flexibility in the process to adapt to changes in requirements, perceptions and expectations.

It was pointed out by the NLC that some specific criteria had been included in Schedule 1 of the Settlement Deed, such as achieving given C:N ratios in topsoil. However, the view was expressed by the NLC that perhaps the company viewed achieving specified standards as too onerous and unworkable preferring a more simple/generic approach to gauging revegetation success. In response to a question as to whether any part of the rehabilitation has achieved a positive result in the minds of the Traditional Owners, the NLC considered it still to be early days but that the general feeling was one of pessimism with not a great deal of confidence in the company getting it right. However, although the Supervising Scientist agreed that perhaps community expectations might not be too high, it was important that the Traditional Owners be made aware that there had been no impacts on the environment or on health as a consequence of mining and rehabilitation at Nabarlek. In particular, radiological safety and environmental protection was reassured and this message had to be properly conveyed to the Traditional Owners.

4 Progress of rehabilitation at Nabarlek (Chair: C Bell, ACMER)

Papers delivered in this session:

Revegetation — PW Waggitt

Rehabilitation at Nabarlek: Erosion assessment — KG Evans, MJ Saynor & GR Hancock

Rehabilitation at Nabarlek: Radiological issues — P Martin, S Tims & B Ryan

Nabarlek: Chemistry issues — G Parker

4.1 Discussion

The appropriateness of releasing the secondary standards (criteria) for Nabarlek at the workshop was raised, however, they are still considered to be commercial-in-confidence.

To a question from the floor regarding access to the site, it had always been understood that access (ie habitation) would be limited after rehabilitation. The assumption, based on previous advice from the NLC, was that the site would be used for occasional overnight camping and be occupied for a maximum of 10% of the year.

In regard to the interpretation of copper concentration in freshwaters, parametric and non-parametric methods for interpreting chemical data could be used. However, there is no baseline data for the Nabarlek creeks and in this instance it would be best to use ecological indicators for assessing impact.

4.2 Some observations from the field trip

Due to lack of time, the field trip was limited to viewing the former ponds area, air strip, grizzly and former laboratories, and former pit area.

- On the former ponds area, good growth of trees and shrubs is associated with higher ground and former walled areas of the pond.
- Grasses dominate the former soil stockpile area.
- The use of subsoil as a surface rooting medium in the former ponds area may be inhibiting growth. B- horizons from the area are known to be unstable and easily dispersible.
- Vegetative cover has improved in the last 18 months over the former ponds area.
- *Melaleucas* are spreading from the pond wall.
- Fire hazard management is an issue. There has been a fire on site every year since rehabilitation commenced.
- Weed grasses appear to be returning more vigorously each year (particularly Mission Grass and Paragrass).
- Around half of the pond area is occupied by low density eucalypts of approximately 1 m height.
- A hot fire went through the former pit area late last year.
- The former pit area is dominated by *Acacia* the majority of which have died from wood boring attack.

4.3 Adams Report

There was consensus that there was a lack of data from which the report's conclusions were drawn and could be verified. The question was raised as to whether the information existed but had not been included in the report. It was felt that both qualitative and quantitative data as presented were difficult to interpret particularly in relation to describing species distribution and patchiness over the mine site. There was a need to examine more than just tree and shrub densities but to look at the age of plants and consider what the information says about the rate of establishment and recruitment. In general, it was felt that the 'overall' summary in the report was highly subjective and could not be justified either on the basis of the scientific evidence presented or by taking account of the short time span since the revegetation of the mine site.

The comment was made that there are many landscape units on the Nabarlek site. One of the problems is knowing how to blend vegetation between these units. However, the interpretation of secondary standards should be based on what is known about the site and its landscape units. There was general agreement that the landforms on the minesite are stable. The point was also made that given that the pond area is on a dolerite outcrop, it would have been useful to have examined analogue sites to help set a baseline. Also, reference to Bureau of Mineral Resources regional studies of the area might provide useful reference aerial photographic evidence of pre-mine vegetation.

There was some disagreement with the statement made in the report that Eucalyptus succession will occur into the pond area. However, the view was expressed that unless they are planted deliberately, it is unlikely natural succession will occur under the prevailing conditions. Mature trees as a seed source would need to be present. It was noted that eucalypts only produce seeds after reaching 10–11 years old.

The usefulness of an organic carbon value as an indicator of revegetation success was questioned. It was more appropriate to consider carbon and nutrient cycling in the context of sustainability and from projected time series data.

5 Indicators of rehabilitation success (Chair: D Williams, CSIRO)

Papers delivered in this session:

Monitoring indicators of minesite rehabilitation success — D Tongway

Termites as ecological indicators of mine-land rehabilitation in tropical Australia — DA Hinz

State of the Environment reporting — J Derrick

5.1 Discussion

The role of ecosystem functional analysis (EFA) as a flexible analytical tool was stressed. Unlike 'traditional' methods of assessment that often have a fragmented framework that can create barriers across disciplines, EFA relies upon an integrated approach to assessing rehabilitation success. It was not enough to simply list ecosystem components and measured values. This tends to be too site specific, rigid and unable intrinsically to distinguish heterogeneity. The effects of inter-seasonal variability must also be analysed.

The point was also made about the need to convey information on the EFA approach to the Traditional Owners and to draw attention to it in terms of 'connection to land'.

6 Closing remarks Day 1 (A Johnston, Supervising Scientist)

It was clear from the workshop that stakeholders hold different perspectives on the revegetation of Nabarlek and that it was the most contentious issue of rehabilitation. Hence, the trust and consensus of stakeholders is a particularly important requirement.

The Adams report, as it stands, is not adequate to reach a conclusion that discharges the mining company from its responsibility of revegetating the Nabarlek mine site. Even if there were data available as unpublished material from the studies made by Adams Ecological Consultants, it would mean that it would still take several more years for a conclusion to be reached about whether the state of revegetation met stakeholders' expectations. At present we are unable to come to a firm conclusion.

Hence, there is merit in looking at the methods that David Tongway has proposed as part of a different approach over the next couple of years. EFA appears attractive because it is straightforward and easy to use and could provide a means of verifying conclusions that derive from traditional approaches that are done in parallel. The NTDME has expressed concern about conducting substantial works on site at this stage but could be assured that the use of Tongway's approach does not require substantial works. Rather it is a case of more data being needed to reach a conclusion which is not a major task. There was also a need to go back to the mining company and ask for the raw data from Adams Ecological Consultants.

Overall in terms of erosion, the site is in a stable condition. No major works are required but the gullies that are present need to be addressed as part of erosion control measures and this is a site management issue. The watching brief by ***eriss*** on erosion will continue.

On radiological issues, the Supervising Scientist was comfortable that exposure routes have been well-defined and that public dose limits are not being breached. There are certainly limitations on access for the future. Some monitoring work is still required to further verify radiological dose, particularly from radon. It has also been recommended that passion fruit vine be eradicated from the site.

In relation to off-site chemistry, the creek systems appear in good condition and groundwater bores downgradient of the former land application area and pit show minor impact. Undertaking biological monitoring on Cooper Creek may be the preferred option to providing assurances to the Traditional Owners that mining impact is not an issue.

There is the need to define a groundwater sampling program (in relation to monitoring and modelling needs) and where necessary maintain existing bores. Groundwater contaminant modelling work using the pit as the source term should be conducted to further verify that the environment remains protected

Day Two

7 Rehabilitation of Nabarlek: Where to from here? (Chair: R Fox, NTDME & A Zapantis, *OSS*)

7.1 Recap on general outcomes from Day One

The general outcomes from Day 1 were as follows:

a) Agreement that the conclusions reached in the Adams report are not supported by the data that it provides. If the conclusions are based (partly) on data that are not appended to the report, the mining company should ask Adams Ecological Consultants for this information.

b) The usefulness and scope for using EFA as an analytical tool in evaluating revegetation success.

c) The need to obtain consensus between parties on the sign-off criteria for a revegetation certificate.

d) The need to peer review the scientific work by Government and administrative bodies in relation to the rehabilitation of Nabarlek.

e) The need to define the 'right data' in terms of assessing revegetation success.

f) The expectations of stakeholders, with regard to the rehabilitation of Nabarlek, need to be process managed. In this regard, the question of what should be reasonably expected after given time intervals should be stated.

7.2 Site management issues (PW Waggitt, *OSS*)

Further negotiation is required between the company, the NLC and contractors to achieve site clean-up. It was noted that the water tank is the responsibility of the Land Trust who are in the process of finding a use for it. One possibility is its acquisition for the Oenpelli water system but access to Oenpelli and cost of transportation are issues.

It was suggested that all infrastructure on the surface and within 1 m of the surface should be removed. The main points are as follows:

(a) Site clean-up

- removal of above and below-ground tanks, cables, conduits, service ducts and concrete pads
- site/soil contamination survey (hydrocarbons, asbestos, heavy metals etc) as previously detailed to the Nabarlek Mine Site Technical Committee

– further infill of grizzly area

– removal of remaining building ruins

(b) Weed control program (see below)

(c) Fire management program (see below)

(d) Feral management program (see below)

(e) Remedial treatment to gullies/deep rills

(f) Repairs to fences

(g) Permanent signage to mark the site of a former uranium mine

(h) Removal of exotic plant species from the former camp

(i) The need for active management implies a site presence.

7.3 Fire impact and management (open discussion)

Preventative fire management was seen as a crucial issue to revegetation success at Nabarlek and based on current practice needs to be improved. In this respect, the time until first burn varies according to vegetation type, growth rate and site conditions. This can take anything up to 10 years. Fire breaks should be maintained until the desired species of trees and shrubs are established. The duration of maintenance depends on the vigour of growth and density of grasses.

Fire can damage diversity. A setback can result in the serious loss of soil organic matter and litter which can mean the system taking up to 5–10 years to recover. However, in the absence of fire, fuel load will increase due to natural mulching and the accumulation of the litter layer. Hence active fire prevention is very important. For example, this means managing grasses to keep out troublesome species such as Damper, Mission and Sorghum grasses that have fast growing rates and dramatically increase fuel loads.

In tropical environments, fuel loads build up quickly and can plateau as soon as three years. At least five years is needed for young eucalypts to withstand fire. Height of trees and flames are key factors but are difficult to predict. In addition, fire intensity (as affected by fuel, season and the heat generated) is an important variable determining the survival of tree species but there are some rules of thumb which can be used to predict damage. For those young trees which survive fire, nutrient stress is common especially on shallow soil and soil stability may be adversely affected as a consequence of humus loss.

Site assessment of fire risk to the success of revegetation should be conducted at least every two years in the early stages of rehabilitation. Assessment should account for plant species, abundance and spatial and age-class distributions from which the potential for fire damage and recovery can be made.

7.4 Weed impact and management (open discussion)

The starting point to weed management at Nabarlek is the collation of a weed species list. Integral to this approach is the assessment of those weed species which are adversely affecting revegetation success and which are listed as control weeds under Territory legislation. For example, *Pennisetum* is known to infest the area and can radically affect fire management programs. Hence, it is important to link fire control and weed management programs and, where necessary, establish vegetation to control weeds. Another important weed on site is *Sida acuta* which is a prescribed weed under the *NT Noxious Weeds Act 1994*. Previously ***eriss*** work in 1993/94, prior to the rehabilitation of the mine site, noted the presence of weed species on relatively undisturbed areas of the mine lease. Thus a weed survey of the lease should account for the possibility of reinfestation within the revegetated former pond and pit areas. It would be advisable to conduct such a survey in collaboration with the annual visit of the NT Government Weed Control Officer to the site.

7.5 Erosion control and management (open discussion)

The issue of the existing infrastructure of roads and drains as a factor in erosion and fire control at Nabarlek was raised. It was unclear whether their deterioration warranted concern. Nonetheless it was agreed that the situation required to be assessed and that the services of a roads engineer from the NT Government be sought. The view of the NLC was that roads and fences should stay, at least in the short term. However, for the longer term, advice would need to be sought from the Traditional Owners. If the roads were to be retained, they would have to be maintained. The point was also made that if monitoring was to continue at Nabarlek over the longer term, road access would be important.

It was felt that some further work was required to determine the risk of further erosion by water from the former waste rock dump area. Simple control measures such as silt traps may be the answer. Research into off-site sediment transport using radiological signatures was continuing.

7.6 Feral impact and management

Pigs, horses and possibly buffalo are the main feral animals on site but numbers are unknown. They have potential to impact upon revegetation success but the degree of damage currently being sustained on site is unknown. One obvious control measure is to repair and maintain the integrity of the existing fence around the site, replace the stolen gates and ensure they are kept closed (locked). The presence of feral animals on site also posed safety problems to visitors and it was in the best interests that the feral animals be removed.

8 An action plan for Nabarlek (Chair: R Fox, NTDME & A Zapantis, *OSS*)

The following represents an agreed position expressed by stakeholders at the workshop.

8.1 Revegetation

8.1.1 More information is required to assess revegetation success particularly its dynamics during this early stage of development.

8.1.2 Amongst the secondary revegetation criteria that might be used to gauge success are species abundance, recruitment, competition, inflorescence, vigour, fire tolerance, weed density and soil C:N ratio.

8.1.3 Adams Ecological Consultants should be invited to supply the raw data missing from their final report but used by AEC to draw their conclusions.

8.1.4 At present, the state of revegetation at Nabarlek does not meet the expectation of stakeholders and the following work is required:

- the landscape of the former ponds area needs to be classified according to surface hydrology to determine which species to plant. In particular, there is a need to determine if some areas are not amenable to tree species.
- where appropriate, the ponds area should be enriched with the interplanting of *Melaleuca* tube stock and seed.
- to assist in the establishment of trees and shrubs, grass should be removed from appropriate land units of the pond area.

- the former pit area shows successful recruitment but requires further assessment of species patterns and densities.

8.1.4 It is recommended that aerial photography be used to delineate upland and run-on zones (which favour *Melaleuca* establishment) and as a tool to assess revegetation success over the whole site. (It was noted that aerial photographs taken in November 1999 are available and that historical information may be held by the Bureau of Mineral Resources.)

8.1.5 Bush tucker plants should not be planted on site.

8.1.6 The scope for including a monitoring program that uses EFA techniques to assess revegetation will be examined by the Supervising Scientist (see section 8.3).

8.1.7 It is recommended that annual assessment of revegetation by the mining company's consultant should continue and be supplemented by information gained from the ACMER project.

8.2 Monitoring

8.2.1 Groundwater monitoring should continue but the sampling program should be designed to not only provide public assurance on environmental protection but used to examine the veracity of model predictions for contaminant movement from tailings. To this end, a program to maintain and repair borehole access should be adopted and, if necessary, new bores sunk.

8.2.2 Allied to 8.2.1, is the need to review the data requirements for modelling and to provide feedback on monitoring requirements and borehole location needs.

8.2.3 Surface water monitoring at Nabarlek should continue.

8.2.4 Radiological dose assessment of bush tucker plant consumption and its risk assessment will be conducted by ***eriss***. Data needs may extend to fish and mussels. Radon emanation monitoring will continue.

8.2.5 An assessment of the risk of erosion in the area south of the former waste rock dump will be conducted by ***eriss*** and, if required, recommendations provided on remedial action.

8.3 ACMER Project

Clive Bell was invited to explain ACMER interests in the rehabilitation of former mine sites and in particular ACMER's support through project work of David Tongway's approach to assessing revegetation success.

He explained that currently a two year project (Stage 1) is nearing conclusion involving the collaboration of industry and regulators in which results from David Tongway's methods have been compared with conventional detailed (classical) methods of assessment on revegetated mine sites. The prime objective of the study is to seek agreement amongst industry, government and community groups on techniques for ecosystem reconstruction and to provide tools to assist in the monitoring and assessment of rehabilitation. In Stage 1, surrogates for indicators that are expensive to determine conventionally were examined. It was Clive's view that Nabarlek represented a strategic and good opportunity to become involved as a test site in Stage 2. He stressed the need to identify the benefits of such a study to the mine company given that David Tongway's technique is a new development that was not available when Nabarlek's rehabilitation started. In Clive's view, it may be strategic for the mining company to have end-points and agreed targets that use scientifically based back up indicators derived from data collected through the ACMER project. This could in turn form the basis for an agreement with the NLC to sign off.

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Annex 1 Nabarlek Workshop Program (18–19 April 2000), Mirambeena Tourist Resort, Darwin

Time	Program	Speaker
Tuesday 18 April		
8.30–8.45	**Welcome & Introduction**	Arthur Johnston (SS)
	History of and Background to Nabarlek	Chair: Alex Zapantis (***oss***)
8.45-9.05	Mining	Peter Waggitt (***oss***)
9.05-9.25	Rehabilitation	Peter Waggitt (***oss***)
9.25-9.45	Discussion	
Morning Tea (9.45–10.00)		
	Perspectives on desired outcomes for rehabilitation at Nabarlek	Chair: Arthur Johnston (SS)
10.00–10.20	Traditional Owners' perspective	Brendan Lewis (NLC)
10.20–10.40	Supervising Authority's perspective	Bob Fox (NTDME)
10.40-11.00	Supervising Scientist's perspective	Alex Zapantis (***oss***)
11.00-11.30	Discussion	
	Progress of rehabilitation at Nabarlek	Chair: Clive Bell (ACMER)
	Commonwealth and NT perspectives	
11.30-11.45	*Revegetation*	Peter Waggitt (***oss***)
11.45–12.00	*Erosion*	Ken Evans (***eriss***)
12.00-12.15	*Radiological issues*	Paul Martin (***eriss***)
12.15–12.30	*Chemistry issues*	Gretel Parker (NTDME)
Lunch (12.20–13.30)		
	Observations from the field trip and other documented material	Open discussion
2.00–2.30	General discussion and conclusions	
	Indicators of rehabilitation success	Chair: Dick Williams (CSIRO)
2.30–3.15	From traditional methods of assessment to ecosystem functional analysis	David Tongway (CSIRO)
3.15-3.45	25 years experience in tropical bauxite mined land rehabilitation	Dieter Hinz (Consultant)
Afternoon tea (3.45–4.00)		

Time	Program	Speaker
4.00–4.30	State of the Environment	Jim Derrick (EA)
4.30-5.00	Discussion	
	Closing remarks	Arthur Johnston (SS)
Wednesday 18 April		
	Rehabilitation of Nabarlek: Where from here?	Chair: Alex Zapantis (***oss***) & Bob Fox (NTDME)
8.30–8.45	Recap on outcomes from Tuesday Workshop	
8.45–9.00	Site management issues	Peter Waggitt (***oss***)
9.00–9.20	Fire impact and management	Open discussion
9.20–9.40	Weed impact and management	
9.40-10.00	Feral impact and management	
Morning tea (10.00–10.15)		
10.15–12.20	**An Action Plan for Nabarlek**	Chair: Arthur Johnston (SS) & Bob Fox (NTDME)
12.20–12.30	**Concluding remarks**	Arthur Johnston (SS)

Workshop papers

The decommissioning and rehabilitation of the Nabarlek uranium mine, northern Australia

PW Waggitt

Office of the Supervising Scientist, Darwin

Abstract

The Nabarlek uranium mine is located in the Aboriginal area of west Arnhem Land[4] in monsoonal northern Australia and operated from 1979 until 1989. Decommissioning was carried out in 1994–95. Several features of the Nabarlek story are considered unique and offer interesting approaches for consideration in other mine rehabilitation programs.

The Nabarlek ore body was mined in a single campaign during the Dry season of 1979. Ore was stockpiled on a specially prepared site while the mill was built. Milling took approximately ten years.

The final decommissioning and rehabilitation program was developed from the outset of operations as a series of specific component plans. Throughout the life of the mine these components were reviewed at intervals and updated to take account of changes in mine development as well as incorporating the results of site specific research and new technology. The final domed cover over the pit was shaped on the basis of geomorphological research.

The rehabilitation objective, as agreed with the Aboriginal Traditional Owners and the supervising authorities, was to establish a landscape that matched as closely as possible the surrounding areas and would permit traditional hunting and gathering activities to be pursued.

The rehabilitation of the site is progressing and on-going monitoring is in train to establish when the site can be returned to the custody of the Aboriginal Traditional Owners.

Introduction and background

Nabarlek uranium mine is located in the Aboriginal lands of west Arnhem Land in northern Australia, about 300 km east of the city of Darwin (fig 1). The climate of the area is wet-dry tropics with an average annual rainfall of about 1450 mm, which falls between October and April. Storm intensities can be extreme and temperatures are high all year round. Annual pan evaporation averages about 2500 mm.

The natural vegetation is a dry sclerophyll forest dominated by *Eucalyptus* and *Acacia* species with *Pandanus* and *Melaleuca* in low lying or poorly drained areas.

The mill operated from 1979 until 1989 when it was 'mothballed' in anticipation of the discovery of a further orebody in the vicinity which would allow the mill to re-open. This was

4 Arnhem Land is an area where indigenous Australians are able to live a traditional life style with some degree of autonomy. They are referred to as the Traditional Owners of the land and control development through Land Councils.

in response to the 'three mines uranium policy' of the Commonwealth Government of the day which forbade the opening of any new uranium mines.

Decommissioning was undertaken through the Wet season of 1994–95. Rehabilitation and earth works were carried out in the 1995 Dry season with seeding taking place just before the onset of the 1995–96 Wet season. Several features of the Nabarlek story are unique, offering interesting approaches for consideration in other mine rehabilitation programs.

History of operations

The Nabarlek orebody was discovered in May 1970 by Queensland Mines Limited (QML), a small uranium exploration company. The deposit was identified as a small, high grade pod, and was excavated by QML between April and October 1979, within the one Dry season (UIC 1996). Ore reserves were estimated to be 606 700 tonnes containing approximately 12 000 tonnes of U_3O_8 at an average grade of about 2%. Waste rock totalled about 2.3 million tonnes. The ore was stockpiled on a custom-built pad with a 400 mm thick ferricrete and gunnite (sprayed-on sand-cement mortar) cover (OSS 1981). The cover was to reduce radon emanation and prevent erosion by wind and leaching losses through percolating water. The runoff from the whole pad area was retained in a pond and then evaporated during the Dry season.

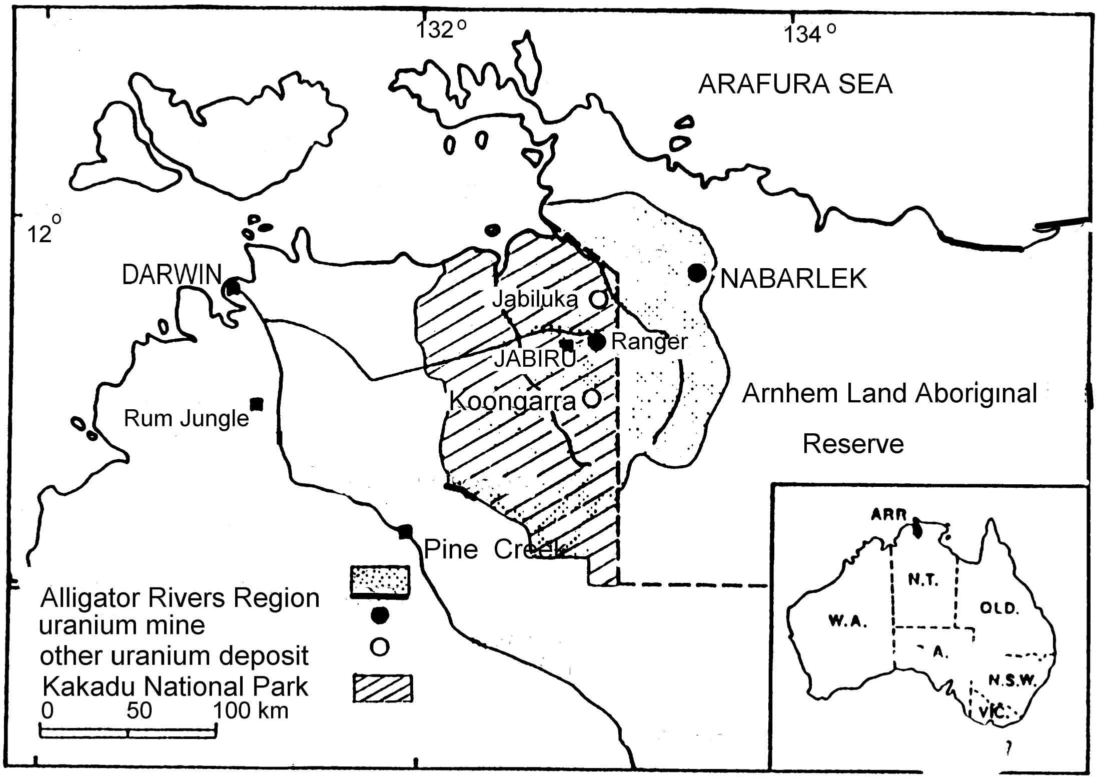

Figure 1 Location map

The processing plant was built following mining; trial commissioning began in May 1980 with commercial production being licensed on 22 August 1980. The initial process used pyrolusite as the oxidising agent in the leach circuit, but by late 1980 the plant had been modified to use Caro's Acid (a mixture of hydrogen peroxide and sulphuric acid), which obviated the need for manganese in the operation with positive environmental benefits. By the time the mill ceased full time operations in June 1988, total production totalled 10 857.6 tonnes of U_3O_8 (OSS 1988).

A significant feature of the operation was the return of tailings directly to the mined-out pit. It is still believed to be a unique occurrence in uranium mining in the world. This was in accordance with the Environmental Requirements (ER) of the Federal Government of the Commonwealth of Australia — a set of conditions put in place to ensure that the operation afforded the environment the highest possible level of protection. The ER were drawn up by the Commonwealth and Northern Territory Governments and the Northern Land Council, acting on behalf of the Aboriginal Traditional Owners of the land.

The ER covered all manner of environmental issues, especially water management, tailings disposal, staff training and environmental impact minimisation. The Commonwealth Government's Office of the Supervising Scientist (***oss***) provided environmental oversight of the operation, and the Northern Territory Government's Department of Mines and Energy (NTDME) regulated the operation. ***oss*** promoted adoption of Best Practice Environmental Management and with NTDME contributed to technical discussions to determine solutions to environmental management issues. In particular, the disposal of excess water from the mine site during the decommissioning was achieved using management techniques recommended by ***oss*** and NTDME staff.

Operations

The planning of the decommissioning and rehabilitation began with the operation of the mine. From a very early stage there was a decommissioning engineer on the staff who had responsibility for not only developing the necessary plans but also updating them to take account of changes in operations and technology. The documentation for the decommissioning was essentially a three tier system. In the first tier the general principles were set out in the deeds and agreements with the mining company, the Aboriginal traditional landowners and the Commonwealth and Northern Territory Governments. In the second tier was a set of broad based plans that determined the general pattern of works and specifications for a variety of activities, including earthmoving, water management, revegetation and erosion control works. The third tier was detailed specifications and contract documents to be used for each stage of the works program. The overall program was costed from the second tier documentation for the purposes of setting the rehabilitation bond.

Site decommissioning and rehabilitation

Site cleanup

The first operations in site decommissioning were the running down of the mill and cleaning out of pipes etc as a mothballing operation. This work was carried out by the mine staff and was intended to leave the mill ready to be reactivated should a further deposit become available. This work was completed by the end of 1989.

The mining company attempted to sell the mill facility on an 'as is where is' basis. The effort was unsuccessful and the company was obliged to decommission the site itself.

The main task of decommissioning the site began early in December 1994, at the end of the Dry season. The successful contractor took possession of the site before the area became cut off by road for the Wet season.

Once equipment was on site dismantling began. Items were thoroughly checked by a radiation safety officer at all stages of the works program. A code of practice for radiological safety had been set up by the supervising authorities and all items were checked against the appropriate criteria. As much as possible was to be salvaged for sale. Some items could not be reclaimed due to high levels of contamination or the practical problems and costs of decontamination when compared to possible re-sale value. Non-salvageable items were placed in the pit to be buried below the base of the final cover. The site work continued throughout the Wet season with the workforce operating on a 'fly in, fly out' basis.

Work was completed in the early Dry season of 1995. Once the road had opened at the beginning of the Dry season, the dismantled mill was transported off-site after further de-contamination checks. The mill was sold to an equipment broker for disposal.

The mine village was handed back to the Traditional Owners of the land who chose to sell the buildings to a number of contractors in 1996. The final clearance of the village site was expected to be complete by December 1997.

Tailings

Tailings deposition at Nabarlek had initially been sub-aqueous, to reduce the perceived risk of radon emanation from the tailings surface. In 1985 the company was permitted to change to a sub-aerial deposition system which allowed the beached tailings to settle at greater average densities. However, the previous system left lenses of slimes and fine materials throughout the tailings mass that were susceptible to differential settlement.

In September 1988 the tailings rehabilitation program began with the insertion of vertical 'wicks' to drain the mass and aid consolidation. The first stage was to place a double thickness geotextile cover across the tailings surface once it had become dry enough for workers to walk safely across the site. A layer of graded waste rock and sand was then placed over the cover to provide a working platform. This layer was designed to be 1 metre thick but due to differential settlement in places this varied up to 3 metres. The material was dumped at the edge of the pit and pushed out over the cover by a small bulldozer. A 'wave' of displaced material advanced in front of the operation and eventually became a raised area near the centre of the pit. This was also finally covered with waste rock. Once the working platform had been established the insertion of the wicks began.

A modified piling rig was used to push the wick material down into the tailings on a grid approximately 3 m by 3 m. A specially made mandrel fitted to the shaft of the rig held the wick material which was pushed to a maximum depth of 33 m. In most cases water was expressed from the wick almost immediately, indicating relief of pore water pressure at depth in the tailings. Water coming from the wicks was allowed to run to a low lying portion of the surface. This water was then pumped to an evaporation pond via the pit water clarifier. The pumping was carried out only in the Dry season (Waggitt 1989).

Water continued to run from the wicks at intervals over the following years right up to the time when the pit was being filled at the final stages of decommissioning. Each time material was deposited in the pit area, the wicks were re-activated by the increased surcharge. Excess water was managed by an enhanced evaporation system which irrigated water around the edges and inside walls of the pit. This water was recirculated and no runoff was permitted to leave the pit area.

Water management

The minesite had been designed as a ‘no-release’ operation with substantial evaporation ponds constructed to ensure that all accumulated waters could be evaporated on site with no need to discharge to the off-site environment. However, it had been calculated that the pond system might have to be operated for 2 or 3 years after the end of operations in order to clear all excess water from the site (OSS 1986).

A trial of land application of evaporation pond water was carried out in 1984 to see if this could be used to speed up the rate of water loss from the site. The option of controlled discharge directly to the adjacent creek system was not considered to be viable at the time.

The trial involved sprinkler application of water to about 1.6 ha adjacent to the airstrip. The only change detected was slight elevation of levels of sulphate and nitrate in the ground water. As a result, in 1985 the operation was extended to an area of 10 ha. In 1986 this area was further extended to include an additional 10 ha of natural forest land. Although the initial trial had been considered successful, the extension into the forest produced adverse impacts. By 1987 some tree deaths had been observed in the forest area and the levels of sulphate and nitrate in the ground water had increased noticeably. Investigations were put in place and it became apparent by 1988 that significant numbers of trees were either dying or showing symptoms of stress which would result in death. Attempts to ameliorate the area by applications of borewater were only moderately successful and tree deaths continued. Irrigation of evaporation pond water was discontinued.

By 1990 the area’s vegetation was markedly different from surrounding areas, with many dead trees. The decision was taken to clear all dead trees to reduce the fuel load as seasonal forest fires, common in the area, were likely to be extremely hot and so have a very severe impact on the re-emerging vegetation. The area was re-seeded after the clearing and allowed to recover naturally.

By 1997 the area was showing considerable re-growth by a wide range of species. The long-term prognosis for recovery is good.

Pond management

The evaporation ponds contained waters whose quality varied considerably with the seasons. As a first step in decommissioning of the ponds, the sediments were cleaned out in 1990. Clay and silt were removed from the base of all three evaporation ponds and placed in the pit for disposal. This action removed both evaporites and radionuclides and the associated risk of their washing out to the environment. Once completed, this enabled the controlled release of water from the ponds in subsequent Wet seasons. Ponds were allowed to overflow through channels cut in their walls. The overflow levels of the spillways ensured that any salts present were well diluted before discharge occurred. Thus the risk of damage to the environment through salt contamination was reduced to an acceptable level.

In the final stages of decommissioning the ponds were allowed to evaporate to dryness during the Dry season of 1995. As the area became accessible, so earthmoving plant was able to collapse the walls into the base of the ponds, thus not only burying the materials that had been exposed to the impounded water, but also restoring the land form to an approximation of its pre-mining contour. The ponds had been built above ground but with excavated floors in some parts, hence the need for infilling. The final cover over the pond area was waste rock and soil from the stockpiles created during mine development.

Site land forming and revegetation

Pit cover

Conventional wisdom for cover design over uranium mill tailings containments often calls for complex multi-layer designs incorporating radon barriers, erosion control layers etc. The original design at Nabarlek included a radon barrier made from clay materials. During the final design phase it was realised that the tailings would all be below the groundwater table at the end of the operation, which would greatly reduce the potential for any significant radon emanations at the surface. After a series of technical discussions and modelling sessions, the supervising authorities accepted the revised design. The design had no separate radon barrier, but relied on the tailings being below groundwater and approximately 13 metres below ground surface as a means of reducing radon emissions.

Landform

The final landform was designed to look like the pre-mining situation as far as was practicable. This included a low area in the vicinity of the ponds and a small hill over the pit site. The pit cover was left raised to take account of subsidence over time as the tailings consolidated, as well as to shed water. The presence of the wicks in the tailings enabled settlement to proceed very quickly in the initial stages.

The final pit landform was originally designed as shown in figure 2 — a low ridge to the south, with the majority of the cover forming a single slope to the north (Weatherhead & Dyke 1987). Research carried out at the Environmental Research Institute of the Supervising Scientist (***eriss***) showed that erosion risks for the site could be considerably reduced by re-modelling the cover to include a small ridge running SE–NW along the centre line of the old pit area (Riley 1994, 1995). This feature reduced slope lengths to less than 150 metres and gradients to less than 8% — values that research had shown were unlikely to lead to gully formation on areas similar to the Nabarlek site (Riley & Williams 1991). The resultant landform is shown in figure 3.

Later modelling using the universal soil loss equation indicated that the cap would remain viable at the site for at least 10 000 years and erosion studies for the surrounding landforms estimated the tailings would stay contained for at least 100 000 years (Riley 1994).

The overall land surface was left covered with run-of-mine waste rock. The material was mainly schistose materials which had been observed to weather rapidly on the waste rock dump. The dump had become extensively colonised by plants during the mine life. A survey of vegetation found 124 plant species on the waste rock dump, including 40 tree species and 84 herbaceous species (Brennan & Bach 1994). This was despite no seeding, planting or spreading of topsoil having taken place.

At the final stages a deep ripper with a single winged tine attached to a large bulldozer was used to break up any surface compaction due to construction activity over the pond areas. The ripping also assisted rainwater infiltration and hence germination and plant establishment. Some large rocks were pulled to the surface by the ripping operation and these were piled up to provide habitats for small mammals and reptiles which would hopefully re-colonise the site (P Bailey pers comm).

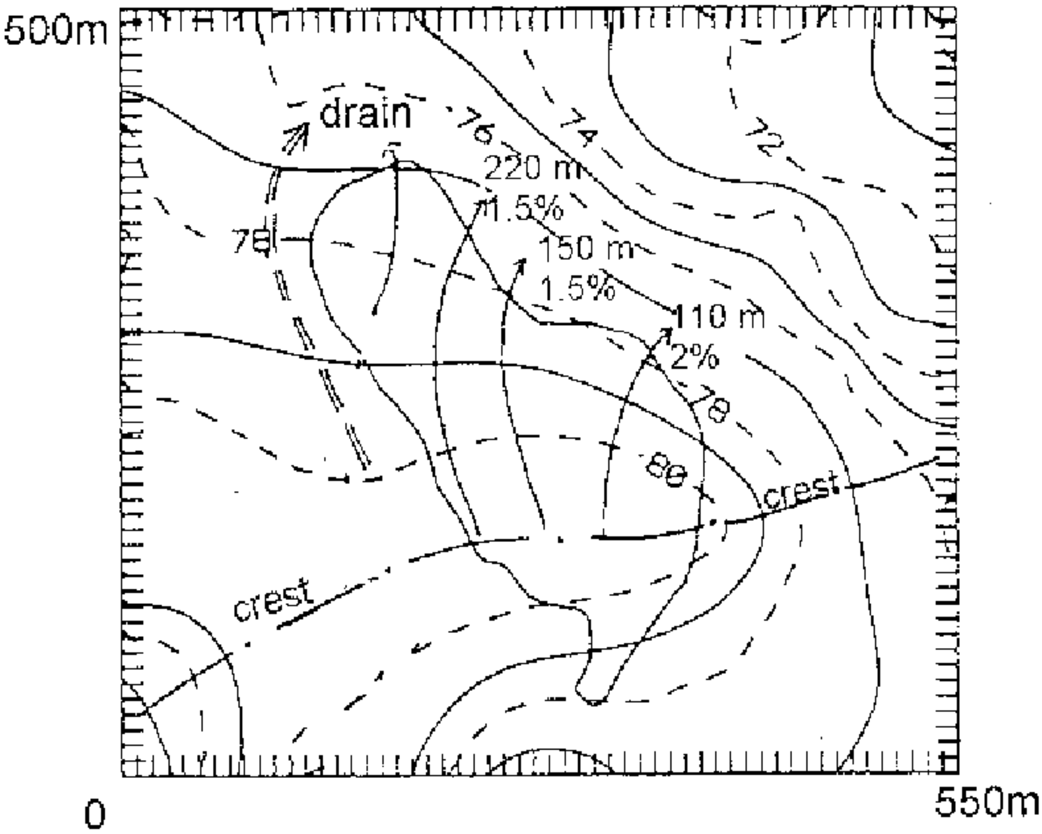

Figure 2 Nabarlek pit cover as designed

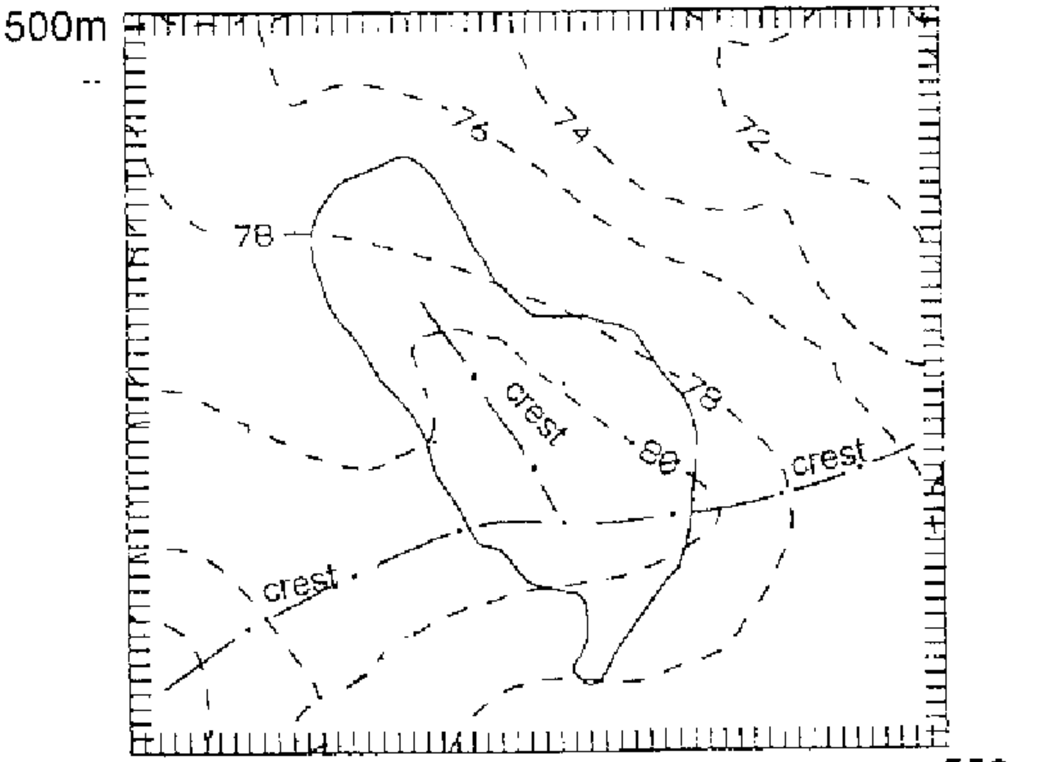

Figure 3 Nabarlek pit cover revised design

Revegetation

As the rock had shown itself to be a good medium for plant growth it was decided to leave it as the final surface, the stockpiled soil having already been found to be of little value as a growth medium (Klessa et al 1995). The overall intention was to leave slopes on the reconstructed surface of less than 1:25, which would aid the rapid establishment of a vegetative cover that would resist surface erosion.

During the life of the mine, research was undertaken into suitable revegetation strategies for the local conditions (Hinz 1989). Trials with locally collected seed showed that direct seeding would be more successful than using tube stock (Queensland Mines Limited 1990). Also, studies showed that several local seed species could not be stored and would need to be collected in the season immediately before revegetation work was to begin (Hinz 1990).

Post closure monitoring

Throughout the operation of the mine and mill the company was obliged to carry out a comprehensive program of environmental monitoring. This included quality of ground, pond and surface waters, radiological measurements, stack emissions, weather recording and some subjective vegetation assessments. A modified version of the program remained in place during the time the site was 'mothballed'. Throughout the life of the site the Northern Territory Department of Mines and Energy, the regulator of the mine, also ran a parallel check monitoring program.

Once decommissioning works began, many of the sampling sites were destroyed by earthmoving etc. As a result the monitoring program was reduced in both scope and frequency of sampling. A vegetation monitoring program using fixed photographic recording points was set up. An independent ecological consultant was appointed to commence an evaluation of the success of the rehabilitation program. The opinion of the expert will be the basis for the decision that the site is reaching the objectives required by the Traditional Owners and the supervising authorities.

The Nabarlek site offers a number of unique opportunities for research and a range of studies are being carried out on the rehabilitated areas. Radon levels are being monitored by the Supervising Scientist Division for a complete year to establish what seasonal variations occur. The Northern Territory authorities are studying groundwater changes in the vicinity of the pit and some work on erosion rates around the site has been planned for the future.

Future and handover

Revegetation at the Nabarlek site appears to be proceeding well and it is anticipated that the self-sustainability of the system will be demonstrated within ten years. Once that stage has been reached the site will be certified by the supervising authorities as meeting revegetation requirements and handed back to the Traditional Owners. The issue of very long-term environmental monitoring has yet to be resolved.

Conclusion

The Nabarlek uranium mine and mill operated for nearly ten years with no significant adverse environmental impact to the off site environment. The tailings were returned directly to the pit in what is regarded as a unique operation. Decommissioning was planned from the first day of operations and updated frequently throughout the entire mine life, taking into account the local situation and incorporating research results as well as technology developments.

Decommissioning of the operation appears to have been successful and revegetation is apparently proceeding well. The probability of the site returning to a condition similar topologically and ecologically to the pre-mining natural state and allowing traditional hunter/gatherer activities by the Traditional Owners, appears high. In such circumstances mining can be seen as a temporary user of land and in tune with ideas of ecologically sustainable development.

Acknowledgments

The author would like to thank his colleagues in the Supervising Scientist Division for their review of the original manuscript.

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Nabarlek Traditional Owners' perspective on the current state of revegetation

B Lewis

Northern Land Council, Jabiru

Aboriginal identity

Aboriginal people derive their identity from an ancestral relationship to land mediated through a traditional form of land title. This relationship to country determines a group or individual's place in the complex of law, ceremony, culture, responsibility, status, marriage, income etc (often collectively termed 'culture'), that is the essential corollary of traditional land tenure. In effect, country bestows upon Traditional Owners a place in the scheme of things as do social and occupational status, racial origin, financial position etc upon the Westerner. It is a critical link in the preservation of Aboriginal society, and pressure on or erosion of this relationship imposes further strain on the significant burden to Traditional Owners of cultural maintenance.

In order that disenfranchisement does not occur because of the mining process, Traditional Owners must have a guarantee that the country will be returned to a pre-mining state as far as possible. This is certainly a significant part of the initial discussion of any consent (under the *Aboriginal Land Rights (Northern Territory) Act, 1976*). Among the worst outcomes for Aboriginal people involved in the mining process is the return to them of degraded lands, an indication to them that the Westerners who initially placed such great value on it no longer do so. These people are left with the mess or the scraps and perhaps for them the least traumatic course is to walk away, to pretend that the mined-out country is of no importance to them and that there is no pain.

Sacredness

Traditional Owners will spontaneously present the metaphor of country as 'cathedral'. An individual exists on country within a sacred space and time not readily explicable in the western paradigm, usually referred to as 'the Dreamtime'. In this Dreamtime, people are contemporary with the creation stories, the ancestral beings are present and the law prescribed by the ancestral beings is in force. It is a spiritually active landscape and the individual's place in it is delineated through tradition and ceremony and subject to various strictures. The modes of behaviour and the law are embodied in the country and transferred to the inhabitants. To preserve their culture, they have little choice but to follow these laws; to not do so is to place oneself outside the law, to become outcast. Pre-contact, the most severe punishment for a lawbreaker (perhaps barring execution) was ostracism — a lingering and lonely death divorced from contact with clan and country.

In the mining context, it should be noted that for Aboriginal people there are often strictures surrounding the disturbance of the ground surface for any but specific purposes. The landscape is often seen as the physical body of ancestors or creation spirits and disturbance of the soil can be considered a wounding of that body which can lead to retribution from the ancestors or creation spirits. This can be translated into a wounding of the body of the present generation — a propagation of disturbance through the spirit — a further diminution of their sense of self. The state of the country reflects back upon a group or individual's own state. There exists a dangerous potential for negative feedback in the interlinked spheres of cultural and social life.

Law

It is difficult to discuss matters of traditional law in the current situation, where in many cases its application has broken down to varying degrees depending on the group under discussion. But this is part of the quandary in which Traditional Owners find themselves in the juxtaposition of the two societies. In cultural surrender, they have no guarantee of admission to Western culture, but by retaining their culture they set themselves at odds with the value systems and material requirements of European culture and the industrial process. Both positions are weighted towards loss. (It is ironic that Aboriginals will confide that their law is strong and immutable, and European law by comparison is fickle and labile. To adjust, they have to accept what they see as a weaker system.)

Co-existing with a European vision of country

Western exploitation of minerals on the other hand is seen as a necessary process of wealth creation. The making of wealth ensures the linear progression of job creation for an increasing population, funds to allow government programs etc. Our basis of land tenure is exploitative and any other form of utilisation is essentially meaningless within a limited interpretation of the industrial process. Enjoyment of the environment aside, we can only extract value from the land — to not do so renders the land worthless and wasted.

This is not to say that the two views cannot co-exist. Traditional land use is also exploitative by necessity. In some cases Traditional Owners are quite happy that Europeans explore and extract minerals from their country. It may be a point of pride that their country is valuable in this way, and that productive work is carried out on their country. Similarly, the derivation of income in the form of compensation or royalty payments is seen as an extension of traditional forms of sustenance on country (notwithstanding the success or failure of employment and training programs). In a sense, the country is still supporting them (though royalty payments in no way match the income of a population in steady employment).

Alternatively, some groups continue to feel the shock of dispossession and refuse to countenance a continuation of the invasion of their lands by Westerners via the industrial process. It should be no surprise that there exists a good deal of resentment and otherwise negative emotion amongst Aboriginal groups towards Westerners. We are seen as a dominating and greedy people who have taken away Aboriginal wealth, the wealth residing in the land. The Crown's appropriation of mineral rights is seen as an extension of this. Many groups find it paradoxical that although the land has been returned to them under the land rights legislation, they do not control subsurface rights, especially in light of the fact that much which is of cultural importance is also subterranean. To these people, land rights is incomplete.

The antipathy of these groups to western exploitation is a mix of emotion and bad experience. Aboriginals who control the land are enmeshed in a two way struggle of rights of access and exploitation. On the one hand traditional access has to be considered and traditional land use nurtured and on the other there is the sometimes constant round of meetings demanded under the legislation to meet the requirements of industry. These determinations of access are tests of power.

It should be recognised that for the Aboriginal person most interactions with Europeans involve some component of power. The past is never far from the present in the day-to-day of a subjugated people. The most positive outcome of these contacts is an unhindered expression of rights, the most negative is the cringing regard offered by the weak to the strong. Under the latter circumstance, commitments made must be adhered to, otherwise the person must admit to obsequiousness, to their own lack of power. In the former circumstance, a statement of rights risks the reapplication of repressive coercion. It is often sadly admitted by Aboriginal people that they must comply with the wishes of Europeans, they cannot stop us, or they are frightened to express opposition, or that events will proceed whatever their position might be. We can only hope that the Nabarlek project will not fall into this category.

To counter this vicious power circle, companies and states involved in the exploitation of traditional lands must strive to accommodate Traditional Owner's interests. A significant component then, of the mining process is the restoration of the landscape to a state that Traditional Owners are happy with. Under this beneficial scenario, all parties can be satisfied at the termination of mining.

Sorry

In considering environmental disturbance, Aboriginal people may say they are 'sorry' for a particular piece of country. The term is funereal in connotation — the same word is used to describe the grief of bereavement. The term may be used to describe country affected by any number of activities: unregulated mining, overgrazing, non-visitation by Traditional Owners, desertion, neglect of ceremonies and traditional land management practices. An abused or untended landscape strikes deep into their souls and this is probably as close as one can really get to an Aboriginal conception of 'wilderness'.

In the longer term, the emotions engendered by a degraded landscape are guilt — the Traditional Owners have failed their responsibilities; grief — the love of the country has been degraded; depersonalisation — within the wider Aboriginal community they become persons without country or persons of scant regard for country; fear — that the ancestral beings will fail to recognise them and will punish them as trespassers. They could not look after their country, whatever the reason, and that is a cause for 'shame' (a generic term covering the whole gamut of intolerable behaviour). Given the interlinked rights to and responsibilities for country shared between Aboriginal groups, degradation of the land is also a potential cause for sanction and punishment. In this context Traditional Owners risk the longer-term blame for the failure of a company to protect or restore the environment.

Agreement making

With the best intentions, parties to the signing of the Deed for recovery of the Nabarlek uranium assured Traditional Owners that the subject land would be returned to its pre-existing condition. Now that the deposit has been exhausted, the miners gone, Traditional Owners are left with country which is not by any means similar in quality to the surrounding country. At present, there is no guarantee to Traditional Owners that the revegetation will be successful. Traditional Owners are waiting for something more to happen with the revegetation program.

In making new agreements Aboriginal people of the region will see the Nabarlek site as foreshadowing what they can expect at the end of the process. In the worst case, people will be making agreements with the expectation that mining will definitely produce a detrimental impact on their country. This would effectively be a continuation of the colonial process and the limited concessions won under the land rights legislation would not be sufficient compensation.

The case of Nabarlek

The rehabilitation of Nabarlek is in some ways a special case. There was a fairly long period from 1988 to 1994 in which nothing happened. At the final decision to close the operation much of the infrastructure was no longer useable. Initially there was ascribed certain value to plant and equipment items that did not really eventuate for Traditional Owners. Significant portions of the remnant infrastructure was handed back to Traditional Owners, which was then disposed through a tender process which in retrospect must be considered lacking in compulsion. But this is a more or less tractable matter compared to the revegetation strategy. Traditional Owners are of the view that the solution is much simpler than the re-establishment of vegetation on highly disturbed ground — essentially as simple as digging a pit and bulldozing the rubbish in.

The NLC has stated that the success or failure of the present revegetation effort has not been satisfactorily determined. It is most unfortunate that the original operators of the minesite were not directly involved in the rehabilitation effort as this would have ensured a more continuous presence on the ground, and some of the apparent problems might not have arisen. To Traditional Owners this transferral of responsibility is most unsatisfactory, the process of encumbrance has no ready counterpart, lines of responsibility relating to country are onerous and compelling and it confirms their perception of the inherent weakness of Western law. In their view, the responsible party is the company which conducted the mining. But in the end, it is a valid component of the Deed to which the NLC is party on their behalf, and a usual feature of commercial agreements. However, it is something that they will no doubt adjust to.

In their own words

In response to a question about people's views on the revegetation:

J Gunwardi — not good. Before (the country) used to be good, but not now. Lots of grass on there — want to see trees growing there.

H Only small shrubs.

J Only little paperbarks. What are they going to do? Put trees on there?

The country has not been returned to a pre-mining state or to a state that resembles the surrounding country. Further discussion included the nature of the soil on the revegetation area and the possibility that it would never support a Eucalyptus dominated woodland. Traditional Owners were accepting of this and indicated that it would be part of their further considerations.

Following discussion of the current revegetation process:

M Are they going to come back and do the job properly?

K Lots of that Mission Grass.

J We feel bad because we thought those fellows would do the right thing for us.

K Somehow getting rid of that Mission Grass.

Traditional Owners are disappointed (and perhaps hurt) that the company has not lived up to its undertakings regarding revegetation. Negotiations were undertaken, and agreements entered into with the assurances that the country would be suitably rehabilitated. The group was advised that it was possible that the company would approach NTDME for a certificate of mine close-out. They maintained that any move of the company towards the grant of close-out would represent to them a breach of faith. This would be regarded as typical behaviour of Westerners (Balanda way — not Bininj way), and though not surprising to them nevertheless quite hurtful.

In response to a question about negative feelings arising from this perceived failure of revegetation:

> H The company should feel guilty. They come and take the land for money and then give it back like that — it makes us feel sad. They shouldn't destroy it like that. If they keep going, where are we going to live? We don't get much out of it. Some people don't care, they just come and take what they want.

> J They have to plant trees there — so that they grow and replace the weeds. We don't like being blamed for lighting fires. Anything that happens, we get the blame.

The question was made to determine whether people were willing to fully disclose their feelings about the country as it is now. It seemed that they were not except to maintain that the revegetation failure was the company's responsibility, not theirs. They expressed unease about the industrial process that it takes no account of their concerns and would ultimately show no regard as to their cultural survival.

Traditional Owners are not happy with the current state of revegetation at Nabarlek. Their impressions are that the revegetation has failed because of insufficient effort on the part of the company. They perceive that the company has more or less abandoned the site. Lack of onsite management has allowed fires to go through the site over the revegetation period and they resent the implication that they are responsible for the revegetation on those grounds. They feel that this lack of management has given rise to the weed problem. They want the company to re-establish an on-site presence to control weeds and fire by spraying (for example) and appropriate fire management.

To Traditional Owners it is obvious and fair that the company should maintain a presence on site. They consider that the efforts to date have not been adequate to the undertakings of the original negotiations. To them it is a simple matter of more work, more on-site presence.

The Traditional Owners were advised that revegetating to a community resembling surrounding vegetation (eucalypt dominated open woodland) was perhaps not a realistic expectation. When presented with the scenario of a *Melaleuca* dominated vegetation resembling a transitional swamp area, the general consensus was that this would be an inferior outcome, but perhaps acceptable under the law of diminishing returns.

That Traditional Owners would accept this inferior outcome is indicative of a realistic grasp of the problems, and a quite generous attitude to the vagaries of human endeavour on a highly disturbed site. It is as much an affront to them that the company would walk away from the site after what they perceive as a fairly minimal effort, as the failure of the revegetation *per se*.

Implications of a worst case

To prejudge Traditional Owners responses to the company's release from responsibilities for revegetation, it is most probable that the messages Traditional Owners would take away will be 'Don't trust the Balandas to revegetate after mining — look at Nabarlek'; 'Don't listen to what the Balandas say, they can't be trusted, they lie to get onto country, and they'll leave their mess behind;' 'Don't trust the Balandas to respect our views — they never have and they never will'.

In effect, a premature abandonment of the site probably will reinforce the negative stereotypes that Traditional Owners have developed over the years of interaction with Westerners. Those stereotypes put the Balanda as untrustworthy and disloyal. They are stereotypes that are laced with discomfort, unequal power distribution, submission, contempt, disregard and so on. They are as widespread and as easily fortified as those held by Westerners against Aboriginals. The minerals industry has been concerned about these very sentiments and has made substantial headway in providing a more beneficial model in recent years.

Nabarlek is the first mine subject to the close-out provisions of the Mining Act on Aboriginal land. A failure to hold the company to a best achievable revegetation effort would be a failure of the mining process on Aboriginal land. Traditional Owners maintain that there remains work to be done on the site to bring it to an acceptable standard of revegetation. Their expectations are not unreasonable, they want to see a more cohesive effort on the part of the company, an ongoing presence that will ensure the most appropriate management strategy for revegetation. They are quite willing to take the inherent difficulties of the site into account, but do not consider that the effort to date has been in accord with commitments made by the industry in general, and the company in particular.

Similarly, were close-out to be issued to the company, the land council would be unable to provide other traditional owning groups with the same level of assurance that country subject to mining will be restored to an original condition. It is likely that other groups facing exploration and mining on their country will want to visit and inspect Nabarlek and talk to the Nabarlek Traditional Owners about mining and rehabilitation outcomes. It should be noted that notwithstanding any agreements between the company and the NLC, the regulator is required to make an assessment of the revegetation to date, in the interests of the industry and the general public whose interests it is bound to uphold.

Conclusions

The NLC has consulted with Traditional Owners as to their views on the current state of the Nabarlek revegetation. Traditional Owners have stated that they are not satisfied with the revegetation to date, and wish the company to increase their future on-site presence as compared to recent years. They have indicated that they are cognisant of site difficulties such that they do not necessarily wish to hold the company to strict revegetation standards. They demonstrated a pragmatism that will allow the derivation of standards suitable to the prevailing conditions of the site, as determined by appropriate research.

Nabarlek rehabilitation: The Supervising Authority's perspective

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Background

Planning for decommissioning at Nabarlek was an integral part of the project design as presented in the Queensland Mines EIS in 1979 (Qld Mines Ltd 1979. From the commencement of the project the company employed environmental rehabilitation officers and set up a nursery to germinate and produce local seedlings for revegetation. Consultants were engaged to undertake flora and fauna studies and revegetation trials were commenced in topsoil and surplus materials stockpiles.

After about five years of operations, around 1984, the Nabarlek Decommissioning Working Group was established. The Group included representatives from the Queensland Mines (QML now QMPL), Northern Land Council (NLC), Office of the Supervising Scientist, NT Department of Mines and Energy, Conservation Commission of the NT, and Water Division. The functions of the group as agreed at its first meeting on 8 February 1984 were:

- To ensure best practicable technology is used in the Narbalek decommissioning plan;
- Queensland Mines Ltd to formulate the plan;
- Other members to provide technical advice to statutory approvers relating to the plan.

Also agreed at that meeting were the operations of the Group including the statement 'Paper work to be minimal' (NTDME files). For reasons that will become apparent later this proved less than helpful. Three years later, the minutes of the meeting on 26 February 1987 recorded: 'The meeting could not agree on revegetation standards for Nabarlek'.

In fact, the group could not agree on two critical issues: how to get rid of the excess water from off the mine site during or after decommissioning and the development of workable revegetation standards. In 1988 the mine was 'mothballed' pending the development of another ore body at which time those areas which would not be necessary in any further development were rehabilitated.

In the Nabarlek EIS, QMPL undertook to evaporate all water from the site and estimated that it could be achieved by year 16 of operations (Qld Mines Ltd 1979). The Company, anxious to leave the site after it was clear that further mining would not be permitted, indicated that evaporation was not sufficient to remove all water from the ponds and began exploring alternatives including:

- Flood irrigation adjacent to the airstrip;
- Spray irrigation next to the airstrip;
- Irrigation of the areas adjacent to Kadjirrikarmarnda Creek.

The results of the irrigation trial were, as everybody at the Workshop would be aware, less than satisfactory because the natural vegetation had difficulty coping with the saline water leading to tree deaths. There was also some suspicion that many of the mature plants had become waterlogged.

QMPL finally made application to release water directly into Cooper Creek. This was initially supported by OSS based on the results of toxicity testing, but not by NTDME or the Traditional Owners and ultimately the company was forced to use evaporation as the only option for disposal of the remaining water.

The point is that the issue was resolved not by the Decommissioning Working Group but directly by the major stake holders.

The issue of close-out criteria for Nabarlek

Early in the Nabarlek project, the company set up an extensive nursery and employed a revegetation officer to undertake studies within the project area (Buckley 1987). The old plant and the temporary campsites were revegetated fairly successfully in the early 1980s. In 1984 it was expected that the newly formed Decommissioning Working Group would establish close-out criteria for the site but the Group met for years without resolving this central issue. The failure was primarily due to the fact that a simple index of success could not be agreed as each scientific ‘expert’ consulted had a different opinion and there were as many opinions as there were experts.

The company endeavoured to break the impasse with a proposal to complete a decommissioning program to be approved by the supervising authority. The outcome of that proposal was that the program should also be the responsibility of the approver and that the company should be given close-out upon implementation of the approved work program. Not surprisingly this proposal did not gain acceptance!

In another effort to break the impasse a general understanding was reached whereby if a consultant, chosen by the four stakeholders, said that the site was stable, all parties would respect that assessment. This would allow for some subjectivity in the assessment and it would limit the number of conflicting opinions. It is not clear exactly when this understanding was reached presumably because of the group’s maxim to keep the paperwork minimal. Recording of minutes of the meetings appears, from NTDME file records, to have been patchy to say the least. However, the following is known and verifiable from NTDME file records:

- Agreements were made between QMPL and the NLC, which defined in generic terms rehabilitation criteria for the site. The first of these was the original mining agreement on 22 March 1979.
- Site specific revegetation goals were agreed between QMPL and the NLC in October 1987 and this agreement was progressively modified through an exchange of letters between the two parties until at least February 1988.
- A settlement agreement on 23 November 1993 between NLC and QMPL required the company to rehabilitate the site ‘in accordance with the standards, principles and objectives set out in the Nabarlek Revegetation Standards …’ ‘until the Supervising Authority issues a certificate of revegetation pursuant to paragraph 27(c) of the Environmental requirements’.

- The summary record of the 12th meeting of the decommissioning group on 12 June 1992 included the statement ‘Agreement in principle was reached that a group of experts could be found who would pronounce on the efficiency of the final rehabilitation’.
- A letter dated 26 July 1994 from the Director of Mines stated *inter alia* that ‘It has already been agreed that a panel of experts will certify successful rehabilitation. It has been accepted that numerical standards will not be imposed and there seems no reason to revise that position.’
- The Manager of Queensland Mines quoted the Director’s statement in a letter to the Supervising Scientist dated 17 August 1994.
- QMPL, in July 1996, agreed with the NLC to appoint Dr Mark Adams of Adams Ecological Services to ‘act as an expert with regard to the determination of satisfactory revegetation of the Nabarlek mine site’. Also within that agreement was the statement ‘Both QMPL and NLC will accept as binding the determination of satisfactory revegetation at Nabarlek by Dr Adams acting as an expert’.
- The summary report of the Environmental Performance Review of Nabarlek (EPR5) in July 1996 recorded *inter alia* that ‘Dr Mark Adams was to visit the site in July of that year with a team of four to develop a program of studies in revegetation, biological monitoring and soil development’. It was also stated that ‘Both NLC and QMPL have agreed to abide by Dr Adams’ assessment of revegetation success…’.

The NTDME perspective

The NTDME position in relation to close-out of the Nabarlek mine site is that it accepts the position of the Traditional Owners of the site as has been presented through the NLC. The sequential land use of the site was to not restrict the enjoyment of the Traditional Owners in their use of the rehabilitated site and the close-out criteria were to be the report of the independent assessor. The Department had, however, urged the NLC to accept some of the facilities on the site that could have been used for alternative economic activities. These included a power supply, water supply, office, laboratories, accommodation units and ponds.

It is acknowledged that members of the Minesite Technical Committee expressed reservations about the final report produced by Dr Adams (Adams 1999). However, with the advantage of hindsight, it would appear that the formal role of the MTC in considering the report was possibly questionable, as the report was a consequence of an agreement between QMPL, NLC and Dr Adams. It is presumed that the company tabled the report in good faith and in the spirit of transparency of process. In any event, the only consistent criticism from MTC was not necessarily of the conclusions reached but of the relative lack of evidence presented to support those conclusions.

A group of scientists could not reach agreement in over 10 years on the basic issue of close-out criteria for a relatively simple mine site. NTDME officers working independently produced a set of simple, generic yet powerful close-out criteria in a matter of weeks (Norris et al 1997). The NT Minister for Mines and Energy approved a set of generic Mine Closure Criteria for use on NT mines in 1997 and, with or without the Adams report, it would be difficult to argue that the rehabilitation at Nabarlek does not fulfil those criteria.

NTDME has sympathy with the company’s position in that it has fulfilled its obligations of an agreement with the Traditional Owners. An independent arbiter was sought, the parties agreed to abide by his assessment and now it appears that there may be doubts as to whether the agreement will be honoured.

Conclusion

The inherent danger of this workshop is that all we may achieve is to turn the clock back 15 years. It would be unfair and unreasonable to expect the company to reopen all the uncertainties with respect to close-out when the rehabilitation has been completed.

The role of Supervising Scientist is, of course, acknowledged and NTDME would prefer that the final close-out of Nabarlek is reached with the consensus of all parties. However, delegates need to be clear that there are three major stakeholders at Nabarlek — the landowners, the company and the regulators, that is NTDME. At this stage of the game, relinquishment of the Nabarlek mine lease is primarily a matter for those stakeholders and the formal relinquishment is the responsibility of the Northern Territory Government.

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Nabarlek rehabilitation: The Supervising Scientist's perspective[5]

A Zapantis

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Introduction

Nabarlek is an important milestone in the history of uranium mining in Australia representing the first of the modern day uranium mines to have gone full cycle from inception to reinstatement under a strict regime of government supervision and compliance. Consequently, there are pressures to get it right and at the same time redress the poor public image of uranium mine site rehabilitation that arose from mining activities at Rum Jungle and the South Alligator Valley in the 1960s. As stated by the Chair of the Nabarlek Minesite Technical Committee (8 September 1999), Nabarlek provides:

> (An) opportunity to demonstrate to the world the successful rehabilitation of a uranium mine under world's best practice methods.

Also, the lessons learnt from the rehabilitation of Nabarlek will undoubtedly feed into processes elsewhere, particularly in the Alligator Rivers Region (ARR).

Responsibilities of the Supervising Scientist

The functions of the Supervising Scientist are promulgated in the *Environment Protection (Alligator Rivers Region) Act 1978*. These relate specifically to the effects on the environment of the ARR from uranium mining *viz*:

- undertake research and collect and assess information
- develop and promote standards for environmental protection and environmental rehabilitation
- supervise the implementation of applicable law
- advise the Minister.

The Statutory Authority for ensuring day-to-day regulatory compliance at Nabarlek is the Northern Territory Government. However, the NT Minister is required to consult with and have regard for the views of the Supervising Scientist through Working Arrangements. The most obvious way in which this is manifested is in the forwarding of all company applications (related to uranium mining at Nabarlek, Ranger or the Jabiluka Project) by the NT Department of Mines and Energy (NTDME) to the Supervising Scientist for comment. These comments are then taken into consideration by the NT Minister in making decisions about applications. The relevance of all this to the rehabilitation of Nabarlek is that since Nabarlek lies within the ARR, the Supervising Scientist is duty bound to comment on any

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5 This paper is a summary of a presentation made at the workshop.

application for a *Revegetation Certificate*. In effect, a comment from the Supervising Scientist supporting such an application is a statement that the Commonwealth is satisfied with the environmental standard of rehabilitation at Nabarlek.

Nabarlek minesite rehabilitation: The Commonwealth's expectations[6]

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Introduction

This paper provides a synopsis of the general criteria by which the Supervising Scientist will determine the success of rehabilitation at Nabarlek. The paper also refers to standards that stakeholders, including the Supervising Scientist, are likely to refer to when assessing the progress of rehabilitation.

General criteria and primary standards

To the greatest extent practicable the site should:

- be cleared of all unwanted infrastructure,
- match surrounding countryside and be self-sustaining,
- have a radiation dose potential in accordance with agreements and standards,
- have an erosion rate similar to surrounding areas,
- demonstrate a surface and groundwater quality which is similar to pre-mining,
- be acceptable to the Traditional Owners,
- safely contain all contaminants for at least 10 000 years, and
- require minimal intervention.

The primary standards, against which assessments are made on general criteria being met, include radiological (as set by the ICRP), vegetation (as established by agreement between the Traditional Owners and the mining company), erosion, water quality and aesthetic standards. In relation to the primary vegetation standards, the Supervising Scientist has noted that achieving a level of agreement extended to one where

> it is the landowners expectation that the revegetated areas will consist of woodland communities of natural species that will blend in with plant communities adjoining the Nabarlek minesite area over which they will forage as per their current practice in adjoining plant communities

and that

> foraging will involve day trips for plant food and fauna and access to the revegetated areas; and occasional overnight camping' (QML/NLC 1987 — Confidential report).

[6] This paper is a summary of a presentation made at the workshop.

Secondary standards

Achieving consensus in defining secondary standards is a balance between recognising the need to verify success (or at least that it is assured) and that of releasing the mining company from undue or unnecessary financial burden. By necessity, secondary standards are site specific and, preferably, should be quantifiable although in the absence of measurable criteria (eg aesthetics), objective assessment may be the only option. In broad terms, however, the judgement of when secondary standards are met at Nabarlek will be set against:

- the success of the rehabilitation works,
- the 'blending in' of revegetated areas with the surrounding landscape, and
- evidence that no further active site maintenance or improvement is required to be undertaken by the mining company.

Negotiations between the mining company (QML) and the NLC over the years appear to have established the criteria that would be used to assess the success of revegetation. These criteria include: the densities of trees; the presence of appropriate grass, shrub and tree strata and assemblages; acceptable levels of flowering and seeding; plant health; resilience to fire; and, the presence of bush tucker plants. However, the differences in opinion that have arisen between stakeholders in the assessment of revegetation success demonstrate the need to adequately define an agreed (by stakeholders) set of criteria as well as an interpretive framework.

It is hoped that this workshop will go some way in achieving the consensus needed to confirm these secondary criteria and the framework of interpretation.

Rehabilitation at Nabarlek: Erosion assessment 1999

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Introduction

Decommissioning work and the rehabilitation at the Nabarlek minesite were completed at the end of 1995. Site description, mining history, environmental management and rehabilitation have been summarised elsewhere (Prendergast et al 1999, Martin 2000, Waggitt 2001). Geology, geomorphology and erosion processes of the environs were summarised by Riley (1995). A list of studies undertaken at Nabarlek has been compiled by Saynor (1996).

Tailings were buried in the mined-out pit and capped with waste rock. An erosion assessment of the cap design, using a combination of modelling and analogue estimates, indicated that denudation rates on the cap would be <100 mm ky^{-1} (Riley 1995). Riley (1995) suggested minor design modifications to reduce slope length on the pit cap to improve stability and provide structural integrity for several thousand years. Riley (1995) observed that roads were areas of most severe rill development in the Alligator Rivers Region (ARR) and suggested that rill development (0.2–0.3 m depth) on the pit cap would occur in the early stages of adjustment toward equilibrium but not persist in the long term.

Consequently, as part of the process of assessing rehabilitation success, erosion at the former minesite was examined by ***eriss*** in August and October 1999.

Study methods

A ground assessment of the perimeter of the evaporation ponds, pit and waste rock dump (WRD), unsealed roads to the north and east of the site and infrastructure area was conducted in August 1999. This survey described, quantified (using a tape and rule) and photographed erosion features. No transects were undertaken. In October 1999, a qualitative (descriptive and photographic) survey of the airstrip, constructed drains, unsealed roads to the west of the site, the pit and WRD was conducted. On this occasion, transects of the WRD and pit were taken but the locations of the transects were not surveyed.

Observations

Sites of observable erosion are classified in the following areas: unsealed roads; WRD and pit; constructed drains; and airstrip and other (fig 1).

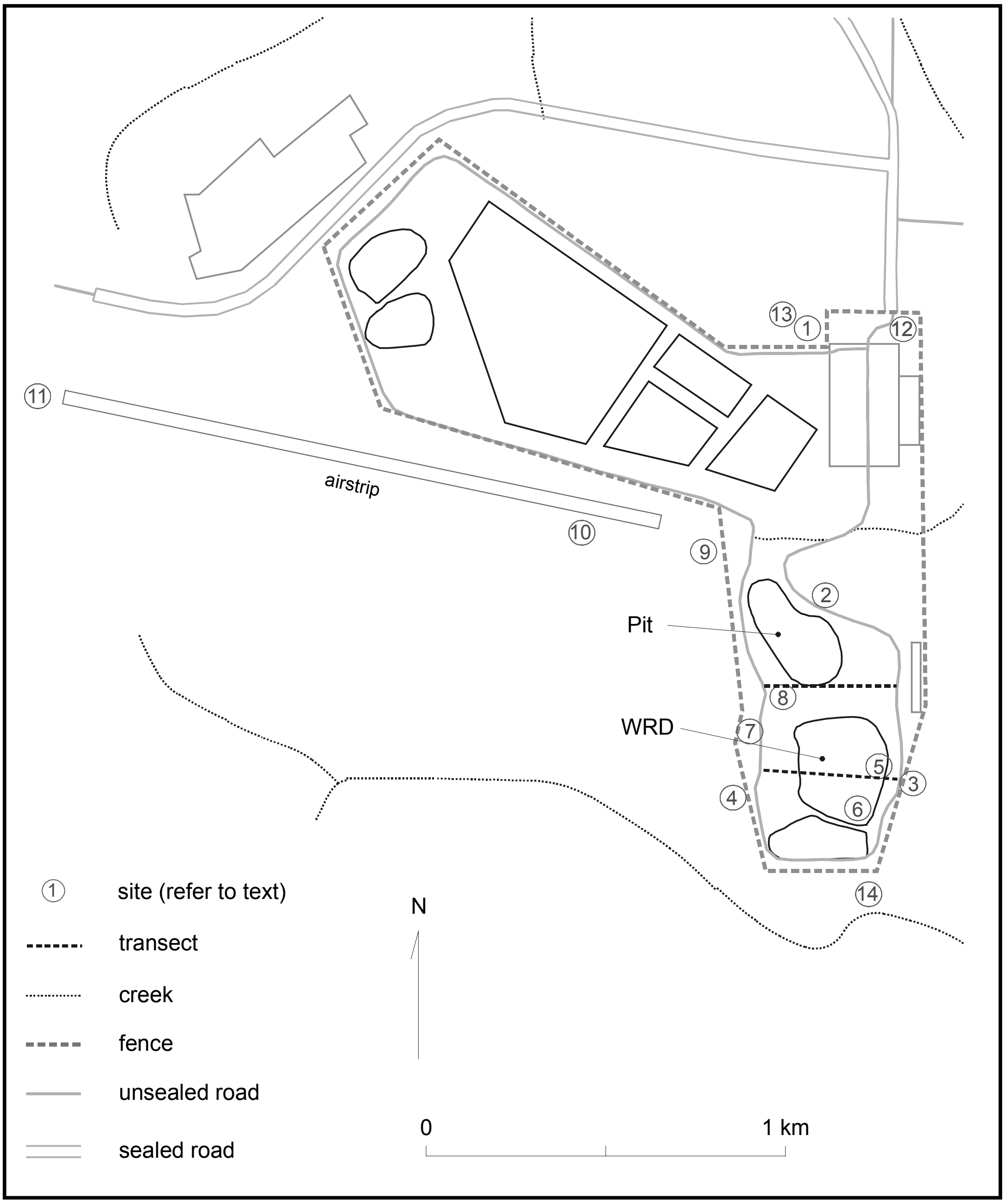

Figure 1 Location of erosion sites

Unsealed roads

Site 1: Discontinuous gullying has developed in the road running parallel to and outside the western fence near the old Telecom tower (plate 1). The gully drains in a northerly direction and is fed by flow from beneath the fence that runs east-west from the office area to the evaporation ponds and the road that runs parallel to that fence. The gully is approximately 54 m long, 1.5 m wide and 1 m deep (maximum) and appears to be active. This gully then debouches into a depositional area where the road turns to the east at 90°. A gully has developed downstream and to the north of the depositional area in an old access road and flows toward Buffalo Creek. It is a series of knick-points and level flood-outs along its 55 m length with a maximum depth of 0.75 m and maximum width of 1.5 m.

Site 2: A series of rills has developed across the road that runs along the northern side of the pit area. The rills are approximately 8.2 m wide at the top of the road near the pit and 5.7 m wide at the bottom of the road leading into sparse scrub. Rills combine into a single rill/gully, draining into sparse scrub, that is approximately 28 m long with a knick-point depth of 0.5 m and a width of 0.8 m. Sediment deposits on to a rectangular fan at the outlet of the gully. This fan is approximately 3 m wide x 10 m long x 0.5 m deep. The field estimated grain size of the sediment is an average 5 mm diameter with some particles up to 30 mm diameter. The gully and fan are well inside the boundary fence. This rilled area was originally photographed in February 1996 and has been repaired at least once since that time (S Tims, pers comm).

Site 3: Rilling has developed on the road next to the eastern side of the WRD. It drains in a southerly direction and is approximately 0.4 m wide x 0.3 m deep.

Site 4: A large gully (plate 2) has developed in the road parallel to and outside the western boundary fence of the WRD. The gully originates inside the fence (see Site 7 below) and drains to the south. The gully continues down the road to the south-west corner of the WRD boundary fence. No quantitative measurements were taken but the extent of the depth of the gully can be seen in plate 2.

Waste rock dump and pit

Site 5: A gully, flowing in a southerly direction, has developed on the waste rock dump (WRD) next to the road on the eastern side of the WRD. It starts near a catchment divide and appears to be fed by rip lines that are not on the contour. The gully runs down-slope to the drainage depression area at the south east corner of the WRD where it then crosses the road toward the boundary fence and joins with the rill described in Site 3. It is approximately 160 m long x 0.8 m wide with an approximate maximum depth of 0.8 m. There is little ground cover vegetation in this area and fire damage to trees was apparent.

Site 6: Knick-point and rill development is present in the south east corner of the WRD (plate 3). This is a small area approximately 0.3–0.4 m deep and 0.5–1.0 mm wide.

Site 7: A gully has developed towards the catchment divide near the up-slope end of the WRD area. It runs in a southerly direction under the fence and incises deeply into the road (see Site 4 above and plate 2) and runs outside the fence down the road to the south west corner of the boundary fence near the waste rock dump.

WRD transect

This transect was walked from west to east across the central part of the WRD. A fire had recently occurred on the WRD and the only ground cover was leaf-fall from severely fire-damaged acacias. The WRD surface is very rough due to large fragments of competent waste rock and surface ripping. There was some minor rilling on the western side of the WRD but there was no sign of rilling or gullying elsewhere on the transect.

Pit transect

This transect was walked from east to west across the area at the edge of the pit near the top of the WRD. No serious signs of erosion were observed except on the western end of the transect.

Site 8: At the western end of the pit transect at the north west of the WRD, ‘badlands’ are developing (plate 4). There is sparse vegetation and four rills/gullies are developing across this unvegetated area. The spoil material in this area has a different appearance (structure, texture, colour) to the rest of the waste rock. The badlands are surrounded by a ripped and revegetated perimeter.

Plate 1 Gully in the road at Site 1

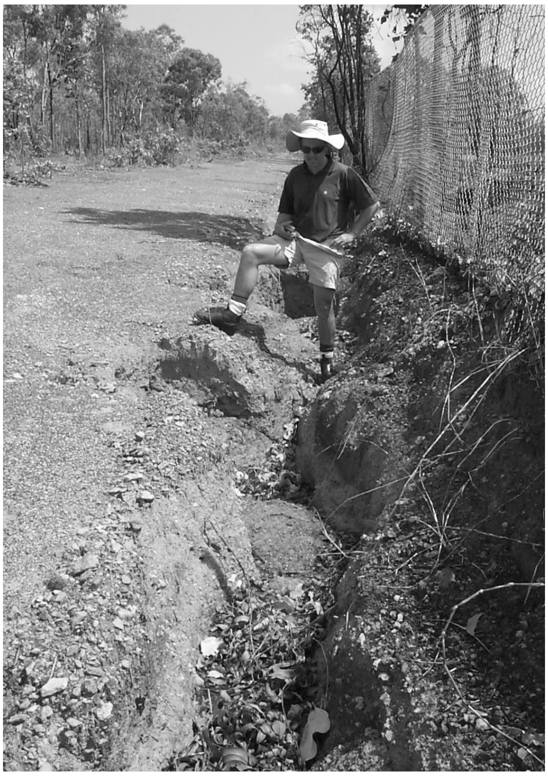

Plate 2 Gully in road at Site 4

Constructed drains

Site 9: Deep incision has occurred in the base of an earth drain that drains the catchment, outside the western fence, to the south west of the pond, north of the pit.

Site 10: An earth drain runs parallel and to the south of the airstrip draining toward the east to the pond at the north of the pit. Severe incision has occurred in the base of this drain (Plate 5). In places this gullying is >2 m wide and >1 m deep.

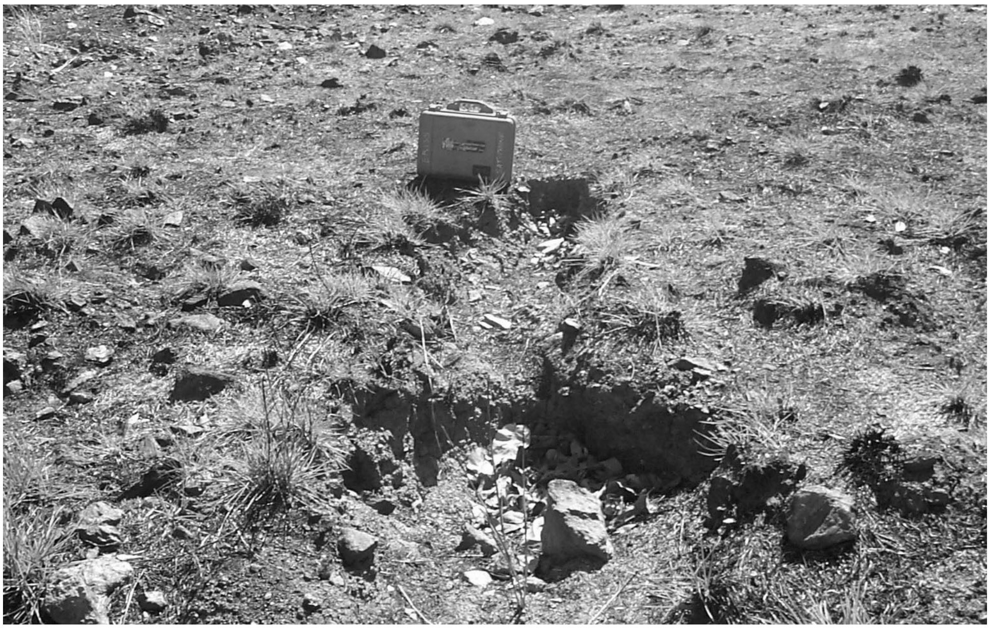

Plate 3 Knick-point and rilling in WRD at Site 6

Plate 4 Rills/gullies near the pit at Site 8

Airstrip and other

Site 11: A large gully >2 m wide has developed at the western end of the airstrip. There is sparse vegetation in this area and pedestal erosion is present on the banks of the gully.

Site 12: An excavation pit has been left to the north of the office area. The excavation pit is several metres wide and 1–2 m deep. There are several piles of earth on the northern edge of the excavation. The sides are unstable and gullies and rills are starting to form at the edges.

Site 13: A ‘borrow-pit’ was observed in woodland outside the northern boundary fence. This is several metres wide and >20 m long.

Site 14: There is a sedimentation pond (Plate 6) outside the south east corner of the boundary fence that receives discharge from the drainage system discussed in Site 3 and Site 5 above. Classic deltaic sedimentation is occurring each wet season in this pond. Coarse gravelly sand and fine mud is being deposited. There is a breach in the south east bund wall of the pond that is approximately 2 m wide by 1.5 m deep and fine sediment has discharged from the pond on to the unsealed road running east-west outside the southern boundary fence next to the WRD. Sediment discharges through the bund breach on to this road where deposition and rilling has occurred. The rill continues for a distance of approximately 50 m in a westerly direction along the road and then crosses the road into woodland where it discharges into a drainage depression leading to Cooper Creek West Branch.

Plate 5 Incision in the base of the constructed earth drain parallel to the airstrip (Site 10)

Plate 6 This is the sedimentation pond outside the south east corner of the boundary fence (Site 14). The breach is seen in the foreground. The bund wall at the southern end of the WRD can be seen at the top of the plate.

Conclusions

As previously observed in the ARR and near the Nabarlek mine site, unsealed roads are the sites of most serious gully erosion. This can extend to any site where the fragile sandy soils have been disturbed, ie in constructed drains and at the western end of the airstrip. Once vegetation has been removed, incision occurs quickly and it is likely a gully will develop. In the Swift Creek catchment, near Jabiluka, incision has been observed in vehicle tracks that have only been used a few times. Incision does not require a constructed unsealed road. An excellent example of this exists outside the fence, several hundred metres to the east of the Nabarlek mine site. A vehicle track in woodland has been deeply incised to several metres wide, is >1 m deep with vertical walls and now appears to be an ephemeral watercourse debouching into Buffalo Creek.

Recommendations

1. Repair all erosion damage to unsealed roads and tracks and implement strategies to prevent their redevelopment.
2. Reassess constructed earth drain design and implement strategies to control serious incision along the base of drains.
3. Repair the gully system on the WRD draining to the sedimentation pond and establish measures to prevent a reoccurrence.
4. Repair and monitor sites of erosion on the WRD.
5. Determine the causes of 'badlands' development near the pit (Site 8) such as spoil/soil chemistry, absence of vegetation and surface form and implement management strategies.
6. Redesign and repair the sedimentation pond so that it can cope with the discharges it is likely to receive. It is not known if the breach in the bund was intentional or whether the design of the pond is meeting expectations.

Research program

1. Detailed assessment of erosion on the site and the likely impacts on the external environment is now being undertaken.
2. The use of airborne and field gamma spectrometry in assessing erosion and sediment transport is being studied.
3. It is recommended that a study be undertaken to assess the rate of infilling of the sedimentation pond and the effects of the sedimentation pond breach on the environment. A study should also be conducted to assess the extent and significance of radionuclide and fine sediment transport from the breach. Erosion rates from the WRD could be determined from this study.
4. A study to determine the influence of the airstrip on local hydrology and its effect on minesite landform stability is recommended.

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Rehabilitation at Nabarlek: Radiological issues

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Introduction

Since 1996 ***eriss*** has been undertaking a major study of the radiological conditions of the rehabilitated Nabarlek site. Since there are no permanently occupied areas on or near the site, present day doses to the public are very low. The major aims of this study are, therefore:

- to provide a detailed radiometric description of the site, so that future users of the area will have sufficient information to judge radiological risk and so that any future study of the site will have a baseline dataset, and
- to provide information that may help in the rehabilitation of other minesites, particularly Ranger and Jabiluka.

Projects that have been completed so far as a part of this study are:

- An airborne radiometric survey, commissioned jointly by ***eriss*** and the Northern Territory Department of Mines and Energy;
- Ground-based gamma (γ) dose rate and γ spectrometric surveys. These were carried out both to give detailed geographic information on γ dose rate and in part to ground-truth the airborne radiometric survey.

Some results from these two projects have been published in Martin (2000). Projects which are presently under way are:

- Continuous measurements of radon concentrations in air (Tims et al 1998);
- Continuous collection of data from a meteorological station;
- Measurement of the geographic variability of radon emanation rate over the site (carried out collaboratively with the University of Adelaide);
- Measurement of diurnal variation in radon emanation rate;
- Measurement of uranium isotopes in groundwater (collaborative with the Northern Territory Department of Mines and Energy);
- Investigation of the transport of material in the Buffalo Creek (collaborative with the Northern Territory University).

Projects which are expected to be carried out in future are:

- Measurement of seasonal variation in radon emanation rate;
- Uptake of radionuclides in edible fruits and vegetables growing on the site;
- Concentrations of radionuclides on airborne dust over the site.

General findings of the research to date

Figure 1 shows the Nabarlek minesite and surrounding areas. The extent of the mapped area in this figure shows the extent of the airborne radiometric survey. Figure 2 shows an image of the 'uranium' (eU) channel data[7] from the airborne survey. Lighter areas in this figure represent higher eU count rates.

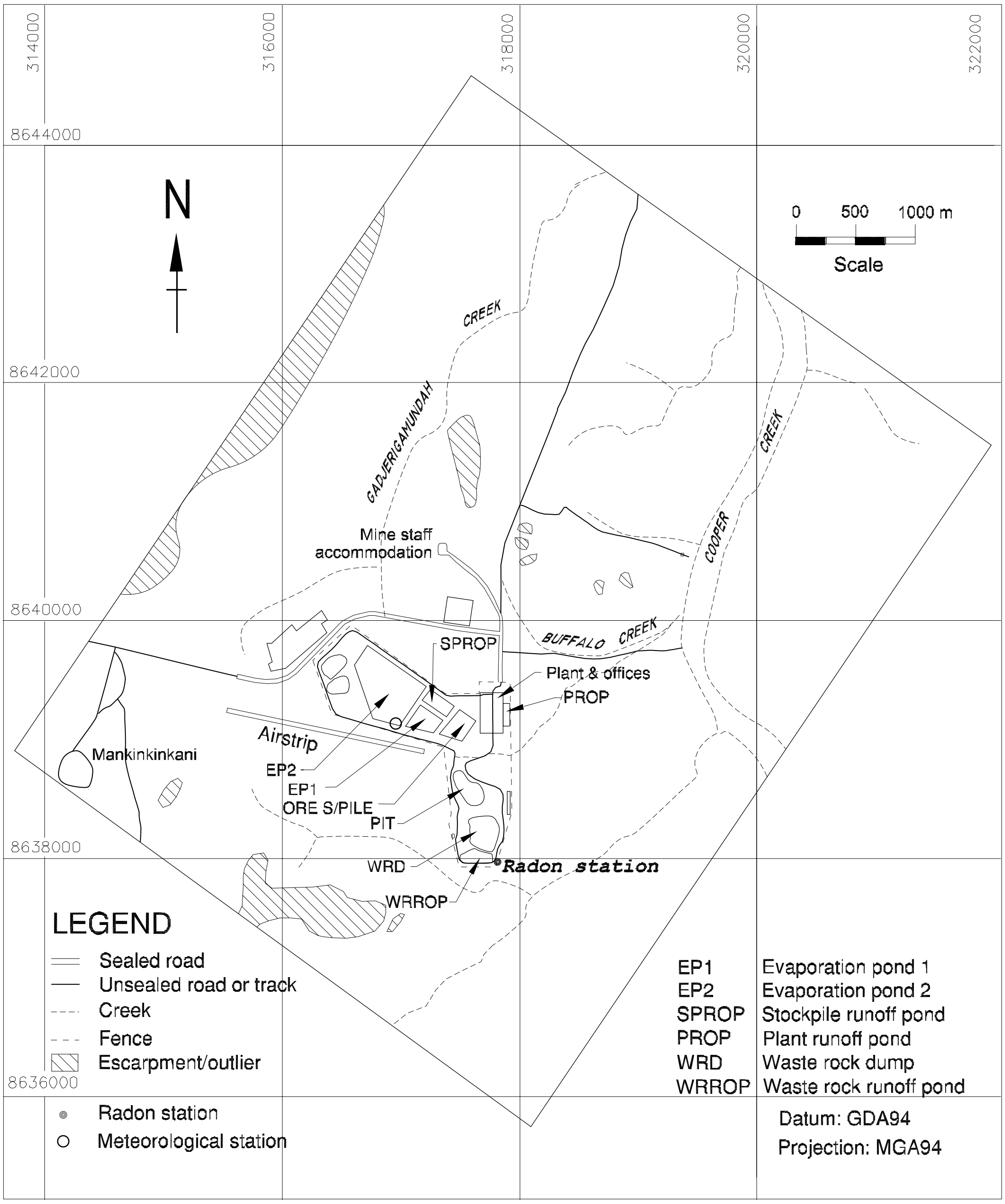

Figure 1 Nabarlek and surrounding area, showing the extent of the airborne radiometric survey

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7 These data may in fact be more accurately considered to be a measure of the uranium-series radionuclide Ra-226 than of uranium itself. For this reason, the symbol used here is eU, for 'uranium equivalent'.

The areas of highest count rate in the airborne eU image are well correlated with features of the former minesite. For example, the location of the small Plant Runoff Pond (PROP), including its north-south orientation, may be easily seen in the eU image. Some other features outside the main minesite fenced area also correlate with elevated eU count rates (though generally at lower count rates than those within the fenceline). These include the Buffalo and Cooper Creeks, and the road to the former Nabarlek staff accommodation area.

The elevated eU signal along the Cooper Creek is probably largely due to deposition of higher-activity silt and clay along the banks. The image shows similar elevated signals upstream of the minesite and along another creek line in the north-eastern corner of the image. As mentioned above, the origin of the activity in the Buffalo Creek immediately downstream of the minesite is the subject of one of the projects presently being undertaken.

As can be seen from figure 2, the eU count rate is quite variable over the minesite, and ground-based γ dose rate surveys have confirmed this fact.

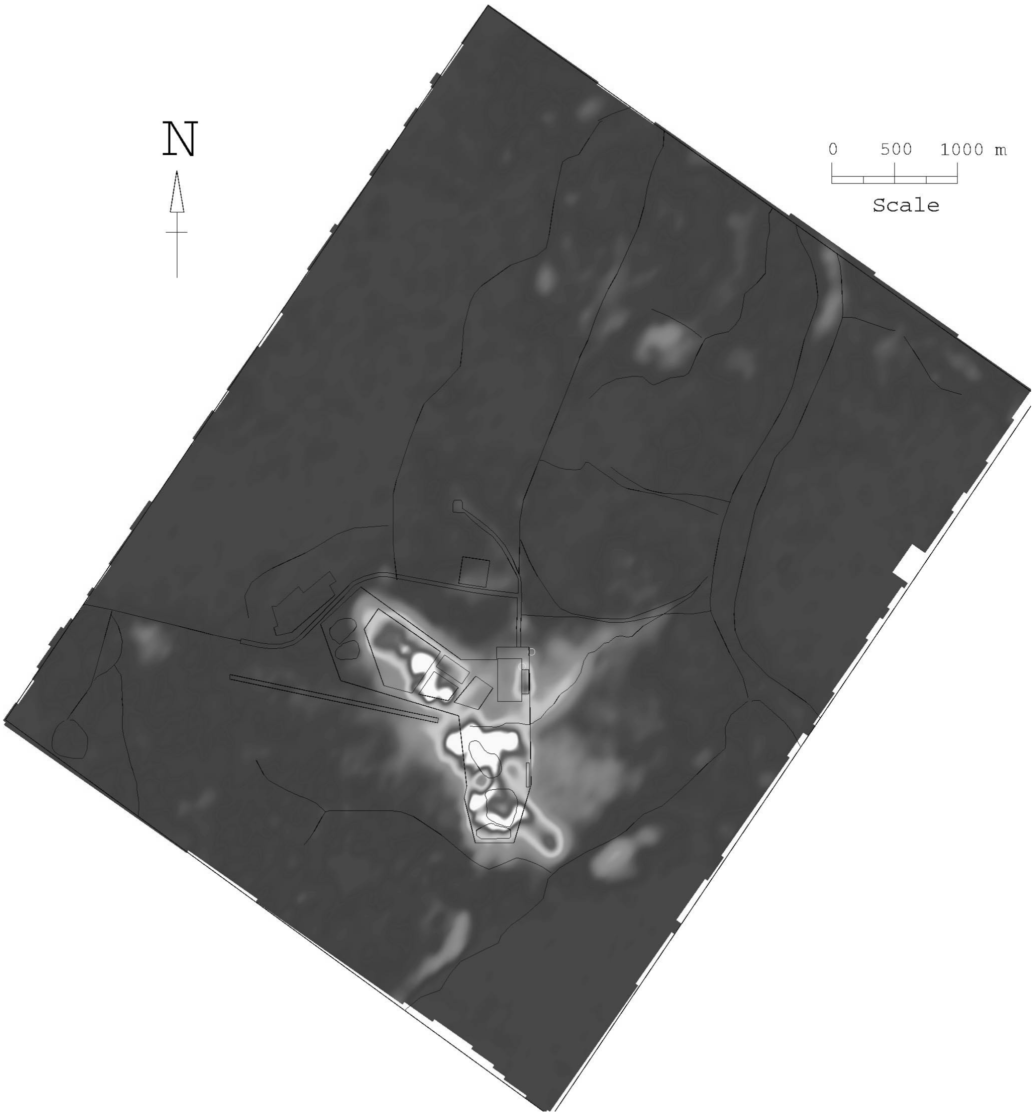

Figure 2 Airborne eU signal as a greyscale image

For example, the present-day γ dose rate (including cosmic ray background) over the former pit area is about 0.9 µGy hr^{-1}, while that over the former evaporation pond and waste rock dump areas varies over the range 0.2–0.5 µGy hr^{-1}. Based on a diagram in the original environmental impact statement (QML 1979), the average γ dose rate over the pit area prior to mining has been estimated to have been 1.7 µGy hr^{-1}. Consequently, the mining operation has reduced the average γ dose rate over this ~5 ha area. However, γ dose rates over the remaining area have been increased. Overall, if we include in the calculation the reduction in γ dose rate over the pit and the increases over the plant/office area, ore stockpile area, ponds, land application areas, waste rock dump and staff accommodation area, then we obtain an area-averaged overall increase of ~0.09 µGy hr^{-1} over an area of ~100 ha (Martin 2000).

As always, predicting actual dose rates to people is highly dependent upon the demographic assumptions used. In the following, two illustrative hypothetical situations will be discussed, the first relating to occasional hunting and camping on the site only, and the second to the building of a house for permanent occupancy.

If we assume a conservative (ie high) rate of occupancy for hunting and camping of 50 days per year, the area-averaged increase of ~0.09 µGy hr^{-1} obtained above, and a conversion factor from measured absorbed dose rate to effective dose[8] of 0.8 Sv/Gy, the resultant above-pre-mining γ dose rate is 0.09 mSv per year. This is much lower than the dose limit for a member of the public of 1 mSv per year applicable for a practice such as a uranium mine. It should be added that other dose pathways have not been included in this calculation. Particularly important in this case would be uptake of radionuclides by food items which might be collected on the site.

The situation is quite different for a scenario in which a dwelling is built on the site. In this case, the use of an area-averaged figure is not appropriate because occupancy would be concentrated primarily in one area. If we conservatively assume occupancy for 300 days per year on the EP2 area, then the predicted above-pre-mining γ dose rate[9] would be 0.9 mSv per year, which is close to the current annual public dose limit. Since other pathways such as inhalation of radon progeny and dust, ingestion of foods, water and soil, etc. have not yet been taken into account and are certain to raise the predicted dose, it is highly likely that the dose limit would be exceeded in this case.

Conclusions

Work on this program of research is continuing. Once completed, the study should allow a reliable dose assessment, taking all pathways into account, to be carried out for any given set of demographic assumptions.

Results obtained so far indicate that use of the area for occasional hunting and camping activities will probably not be precluded. However, it would be inadvisable to build housing for permanent occupancy within the main fenced minesite area.

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8 UNSCEAR (1993) estimate this conversion factor to be 0.7 and 0.8 Sv/Gy for adults and children, respectively. The latter figure has been used here.

9 An indoor occupancy factor of 0.3 has been used in this estimate. Although low by comparison with the norm in industrial societies, it reflects the fact that Aboriginal people generally prefer an open, outdoors lifestyle. The average post-mining γ dose rate above the EP2 area has been measured at ~0.32 µGy hr^{-1}, with the estimated pre-mining figure being 0.1 µGy hr^{-1} (Martin 2000).

In relation to future rehabilitation activities, it would be inadvisable to deliberately plant edible fruiting trees or vegetables on the site, at least until this uptake pathway has been fully investigated. Furthermore, as can be seen in plates 5.47, 5.51 and 5.53 of AEC (1999), *Passiflora foetida* is already present within the minesite area. Ingestion of the edible fruit produced by this introduced vine potentially forms such a pathway. It is therefore advised that this species be either eradicated from the site or its spread controlled until radionuclide uptake by this plant has been adequately investigated.

Results from the airborne radiometric survey show that the main areas of elevated eU count rate are well defined by the Nabarlek fenceline. For this reason, it is preferable that the fence is retained if at all possible, as a visual indicator to people of the extent of the elevated-activity area.

Acknowledgments

The Northern Territory Department of Mines and Energy provided equal funding with ***eriss*** for the airborne radiometric survey of Nabarlek; the idea of undertaking this survey originated with Tony McGill. NTDME also provided the portable NaI(Tl) γ spectrometer used in the ground-based γ survey. We would like to thank Roger Clifton both for this and for his advice on data interpretation. We would also like to thank Bernard Prendergast of ***eriss*** for his advice and for his support of the research program.

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Nabarlek: Chemistry issues

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Abstract

Kadjirrikamarnda Creek continues to show minor water quality deviations from background with respect to nitrate, aluminium, ammonium, sulphate and pH. Bioassay work has shown this water to be of low toxicity to local organisms. Buffalo Creek also displays minor deviation from background (less variation than Kadjirrikamarnda Creek). Cooper Creek does not display any clear trends away from background. All surface waters meet NHMRC (1996) Drinking Water Guidelines for health.

Groundwater bores downgradient of the pit and former Forest Irrigation Area continue to demonstrate minor impact from former operations. All groundwater bores, except OB19, meet NHMRC (1996) Drinking Water Guidelines for health. OB19, adjacent the pit, slightly exceeded the manganese guideline for health in August 1999.

Background

Principle contamination sources — Operational phase

The stockpiling of the ore and the mineral extraction process was the source of virtually all the potential pollutants at Nabarlek. A review of the process chemistry is therefore useful:

Reagents

$$2Fe^{2+} + MnO_2 + 4H^+ \rightarrow 2Fe^{3+} + Mn^{2+} + 2H_2O \quad \text{(before May 1983)}$$

$$\left.\begin{array}{l} H_2O_2 + H_2SO_4 \rightarrow H_2O + HSO_5^- + H^+ \\ HSO_5^- + H^+ + Fe^{2+} \rightarrow Fe^{3+} + SO_4^{2-} + H_2O \\ 2R_3N_{(org)} + H_2SO_4 \rightarrow (R_3NH)_2SO_{4(org)} \end{array}\right\} \text{Remainder of plant life}$$

Process

$$2Fe^{3+} + UO_{2(s)} \rightarrow UO_2^{2+} + 2Fe^{2+}$$

$$UO_2^{2+} + 3SO_4^{2-} \Leftrightarrow [UO_2(SO_4)_3]^{4-}$$

$$[UO_2(SO_4)_3]^{4-}_{(aq)} + 2(R_3NH)_2SO_{4(org)} \Leftrightarrow (R_3NH)_4UO_2(SO_4)_{3(org)} + 2SO_4^{2-}$$

$$4NH_{3(g)} + (R_3NH)_4UO_2(SO_4)_{3(org)} \rightarrow UO_2SO_{4(aq)} + 4R_3N_{(org)} + 2(NH_4)_2SO_4$$

$$2UO_2SO_4 + 6NH_4OH \rightarrow (NH_4)_2U_2O_{7(s)} + 2(NH_4)_2SO_4 + 3H_2O$$

$$9(NH_4)_2U_2O_{7(yellowcake)} \xrightarrow{heat} 6U_3O_8 + 14NH_{3(g)} + 15H_2O + 2N_{2(g)}$$

Minor constituents of the ore included galena, chalcopyrite and pyrite, hosted by amphibolite and chloritised schist. Thus mobilisation of Al, Cu, Pb, and Zn was also possible.

Note that the UO_2 oxidation was mediated by ferric iron, which was regenerated by oxidant addition (pyrolusite or Caro's Acid). The source of the iron is usually dissolution of iron-bearing minerals in the ore although some iron was added at Nabarlek due to the high grade of the ore.

The distribution of the radionuclides ^{226}Ra, ^{230}Th, ^{210}Pb and ^{210}Po in process and waste streams was investigated in some detail (Ring et al 1982). Only 20% of the ^{230}Th present in the ore was mobilised in the leaching circuit; 0.01% of the ^{226}Ra, 0.18% of ^{210}Pb and 0.37% of the ^{210}Po. Ring et al (1982) also considered the efficiency of ^{226}Ra removed by $BaCl_2$, and found that under optimal conditions 98% of the total radium was removed. However, the addition of $BaCl_2$ had only a small effect on the long-term concentration of soluble ^{226}Ra in the presence of tailings. The neutralisation of tailings to pH 8.5 removed over 99% of the dissolved ^{230}Th, ^{210}Pb and ^{210}Po, but the concentration of dissolved ^{226}Ra increased.

There were originally six main structures for water management, which reduced to five in the early 1980s. The two evaporation ponds (EP1 and EP2), plant runoff pond (PROP), the pit and the stockpile runoff pond (SPROP) were decommissioned prior to 1995.

Environmentally relevant events during operations

In 1981, pH in pond waters was noted to acidify despite prior neutralisation. This was attributed to oxidation of ammonium to nitrate with the concurrent release of acidity:

$$NH_4^+ + 3H_2O \rightarrow NO_3^- + 10H^+ + 8e^-$$

This was believed to have been microbially-mediated. Thereafter ponds were regularly dosed with soda ash, lime or hydrated lime. The PROP, which received acid spills from the plant was particularly prone to acidification. Heavy rainfall in March 1981, due to proximity of Cyclone Max, resulted in an escape of restricted release zone (RRZ) water from the PROP and associated drains, the only accidental spillage known from the project.

When the Waste Rock Run-Off Pond (WRROP) was breached in 1983 some silty water was observed entering Cooper Creek west via Billabong D but was not detectable at GS8210024 on Cooper Creek. There are no trends to indicate continued elevation of soil erosion products entering Cooper Creek.

A trial operation of land application of waters from EP1 and EP2 over a 2 ha area commenced in the 1984 Dry season.

In 1985, Cyclone Gretel arrived resulting in an excess water budget. Land application from EP1 commenced over a 10 ha area. In addition, a large slump in the pit wall occurred and permission was obtained to change from sub-aqueous to sub-aerial tailings disposal.

In 1986, land application of EP1 over 20 ha resulted in some tree deaths in the Forest Irrigation Area (FIA) and tree deaths continued to be noted for some years. A 'lime boil' stage was incorporated into the mill circuit at about this time to reduce the quantity of ammonium leaving the plant. Land application management was refined in 1987, with EP1 irrigation restricted to the airport-stockpile area and fresh borewater was applied to the FIA. Borefield C, near the plant, was decommissioned due to rising levels of nitrate and sulphate. Typical water quality results for EP2 in 1987 were total dissolved solids (TDS) 7600 mg/L, ammonium 1380 mg/L, sulphate 6620 mg/L, nitrate 32 mg/L, manganese 5700 µg/L, uranium 45 µg/L and pH 5.44.

The first seepage of tailings water from the pit was noted in 1987 in bores OB19 and OB20, located adjacent the SSE pit wall.

Milling of stockpile ore and tailings deposition ceased in June 1988. The tailings were covered with geotextile, sand and broken rock. Vertical drainage wicks were installed. When the ponds dried out late in November, the floors of SPROP, PROP and EP1 were cleaned out and contaminated clays removed and emplaced in the pit. The PROP was excised from the RRZ in 1989.

Irrigation of borewater on to the FIA occurred in 1989, with limited irrigation of EP2 water occurring in 1989. In 1990 limited irrigation of PROP and SPROP water was allowed. The estimated load of sulphate in the ponds at the end of 1991 was 750 tonnes, of which EP1 and EP2 held 52% and 48% respectively. Volumes of waters irrigated and loads of contaminants have been reported previously.

The directly impacted area at Nabarlek was <200 ha. Soils in the stockpile, airport and FIA were salinised by irrigation waters. However, the sandy soils at the FIA recovered somewhat more quickly than the heavier soils at the stockpile and airport areas. Soil profile data collected in 1988 showed low salinity below levels that would cause tree stress in the 0 to 2 m depth range, while between 3 and 5 m, salinity rose to levels that would cause tree stress (Chandrasekaran 1989). Soil salinity at depth was in equilibrium with the groundwater and would only improve with an associated improvement in groundwater quality (Chandrasekaran 1989).

In 1990, Queensland Mines Ltd (QML) proposed to mothball the plant while further exploration for ore was conducted.

Enhanced evaporation led to EP1 and EP2 becoming dry by September 1992. Subsequently the uppermost 10 cm of the pond floors was scraped in October 1992 and disposed in the pit. The north-west wall of EP2 and the wall between EP2 and EP1 were cut in November 1992. In March 1993, the TDS of ponds and pit had dropped to 390 t compared to 800 t the year before (NTDME 1993). Excess water remaining after the Wet season was pumped to the SPROP and thereafter irrigated to the Stockpile Pad. Excess pit water was irrigated in the pit catchment. Freeflow was allowed after the first flush water had been transferred to the SPROP.

In mid-March 1994, EP2 water, which was within centimetres of overflow, was pumped over the spillway, as allowed under the authorised water management plan. Water quality in EP2 remained below informal criteria (ie EC <2000 µS/cm) (NTDME 1994).

Groundwater

All groundwaters at Nabarlek were originally fresh (TDS <500 mg/L). Four hydrochemical facies can be distinguished based on source of recharge and nature of solid matrix of each aquifer: dolerite, schist, sand and Cooper Creek Alluvium.

Groundwater at Nabarlek is generally considered to consist of two aquifers: deep and shallow. Movement in the deep aquifer is mainly along fractures and at the boundary of weathered and fresh rock. The deep aquifer system generally occurs below 10 m depth. Further details may be found in appendix A.

Contemporary chemistry

The most useful tracers of mine waters at Nabarlek were those species present in much higher concentration and proportions in mine waters compared to natural waters. The most useful simple measure is the EC which was generally much higher in mine waters. Elements enriched by greater than an order of magnitude in the ore relative to surrounding rocks were uranium (228 times), lead (85 times) and copper (15 times) (Noller et al 1985). However, these were all relatively immobile in Nabarlek groundwater and are not useful as tracers. The most useful chemical species were those derived from milling, especially sulphate and nitrogen species (ammonium and nitrate), almost absent in local natural waters and low pH caused by the oxidation of ammonium to nitrate.

The fractured rock character of the deep aquifer of the dolerite and schist rock types means that preferred pathways are very important in controlling groundwater and solute movement, while significant heterogeneity can exist in the shallow aquifer also. This is evident in various borewater quality plots presented in Appendix B.

Statistical analyses has not been attempted using Nabarlek data. In some cases evidence of continued impact is clear and in other cases analyses are difficult because of high temporal variability, poor detection limits and unsatisfactory analytical methods.

Various plots of water quality data are provided in Appendix B. Note that metals (except uranium, manganese and aluminium) mentioned in the ensuing points were measured as totals only. Examination of this data reveals:

- Kadjirrikamarnda Creek continues to exhibit deviations from baseline due to discharge of contaminated groundwater from the former FIA. As the source has been discontinued, both the groundwater in deep and shallow aquifers downgradient of the former FIA and the water quality in Kadjirrikamarnda Creek are improving. Parameters that exceed proposed ANZECC (1999) Level 1 guidelines include nitrate, ammonium, aluminium, cobalt and cadmium. pH and sulphate also deviate from background. Fish community studies and bioassay experiments (van Dam et al 1999) clearly show that waters in Kadjirrikamarnda Creek are of little, or no, toxicity to local aquatic organisms. Shallow groundwaters and surface waters deviate from NHMRC (1996) drinking water guidelines only on aesthetic grounds (pH for both surface and groundwaters, total iron for groundwaters). OB47D, the deep aquifer bore downgradient of the former FIA also slightly exceeds nitrate and ammonium NHMRC guidelines.
- Buffalo Creek continues to deviate from background with respect to magnesium, calcium, sulphate, aluminium, manganese and copper. Given that water quality parameters, other than pH, are similar to those in Kadjirrikamarnda Creek it is expected that this water would have low toxicity to local aquatic organisms. The uranium in table 1 for the Buffalo Creek site may appear to be elevated but is actually a well-recognised natural artifact of this creek. Water meets NHMRC Drinking Water Guidelines.
- Cooper Creek is not showing any clear trends away from background. It would probably be more beneficial, if stakeholders require further reassurance as to possible impact from former operations, to undertake an ecological study rather than an intensive chemical monitoring program. Note that Suggit (pers comm) undertook an AUSRIVAS survey along Cooper Creek in 1995/1996. Water quality meets NHMRC Drinking Water Guidelines.
- Most groundwater bores downgradient of the pit and former pond and stockpile areas continue to show degraded water quality. All but OB19 meet NHMRC guidelines for

health, failing only with respect to aesthetic guidelines (total iron, pH and TDS). OB19 situated adjacent the pit, displays elevated manganese concentrations. Recent ^{226}Ra data are not yet available, but data from 1995/96 indicate radium-226 in all bores is within NHMRC (1996) Drinking Water Guidelines, including OB19. Bores have tended to show some improvement in water quality over recent years.

- Recent ^{226}Ra data are not yet available but ^{226}Ra measured in surface waters in 1996 was <50 mBq/L.

Acknowledgments

I acknowledge the assistance of Peter H Woods in preparing this paper through his comprehensive unpublished review of operations at Nabarlek.

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Appendix A: Groundwater

The deep aquifer is generally overlain by a weathered clayey layer that behaves as an aquitard (semi-confining layer). The soil and laterite overlying the weathered rock tends to be quite permeable, forming a second shallow aquifer. The aquitard separating the two units is discontinuous and in some locations (particularly low-lying areas) the two systems are well connected.

The deep aquifer may be subdivided by the nature of the bedrock in which it occurs. Salama and Verma (1985) considered the following divisions:

- Chlorite — this division refers to a zone of chloritized schist surrounding the former orebody and is of low transmissivity (1–10 m/day/m) (Salama 1986), behaving more as a slightly fractured aquitard;
- Dolerite — underlies the mine site;
- Schist — occurs north of the dolerite band and is overlain by Kombolgie Sandstone.

Under the FIA the shallow and deep aquifers are considered to behave as a single unit. The shallow aquifer largely occurs in sandy soil, which is probably why the EC:TSS ratio is 1.0, 0.95 and 0.90 for the dolerite, schist and Cooper Creek alluvium aquifers respectively, rather than the more common 0.6 to 0.7.

Table 1 Ionic dominance in Nabarlek groundwater facies

Aquifer	Cations	Anions	Transmissivity m/day/m
Dolerite	Mg=Ca>Na	HCO_3>>Cl>SO_4	5–59
Schist	Mg>Ca>Na	HCO_3>>Cl>>SO_4	≤200
Sand	Na>Ca=Mg	HCO_3>Cl>SO_4	10
Cooper Alluvium	Na>Mg>Ca	Cl>HCO_3.SO_4	100

The standing water levels at Nabarlek in both deep and shallow aquifers tend to reflect the topography. Most of the groundwater flows towards Cooper Creek in the east, with Buffalo Creek tracing a higher permeability zone and possibly constituting a discharge zone. West and north-west flow towards Kadjirrikamarnda Creek was known to occur to the west of EP2, including transport of solutes from the FIA (Pidsley 1985). The shallow aquifer has considerably higher groundwater velocity (up to 1 m/day).

Salama and Verma (1985) also noted that if the area surrounding the pit has a high transmissivity similar to schist (ie 200 m^3/day/m) and given the chemistry of the pit is properly controlled, the migration of solutes is not expected to extend further than a few hundred metres surrounding the pit.

Subsurface drains along the western and southern sides of the management ponds were noted to be a sink by Salama and Verma (1985) during operations but have become a source on decommissioning.

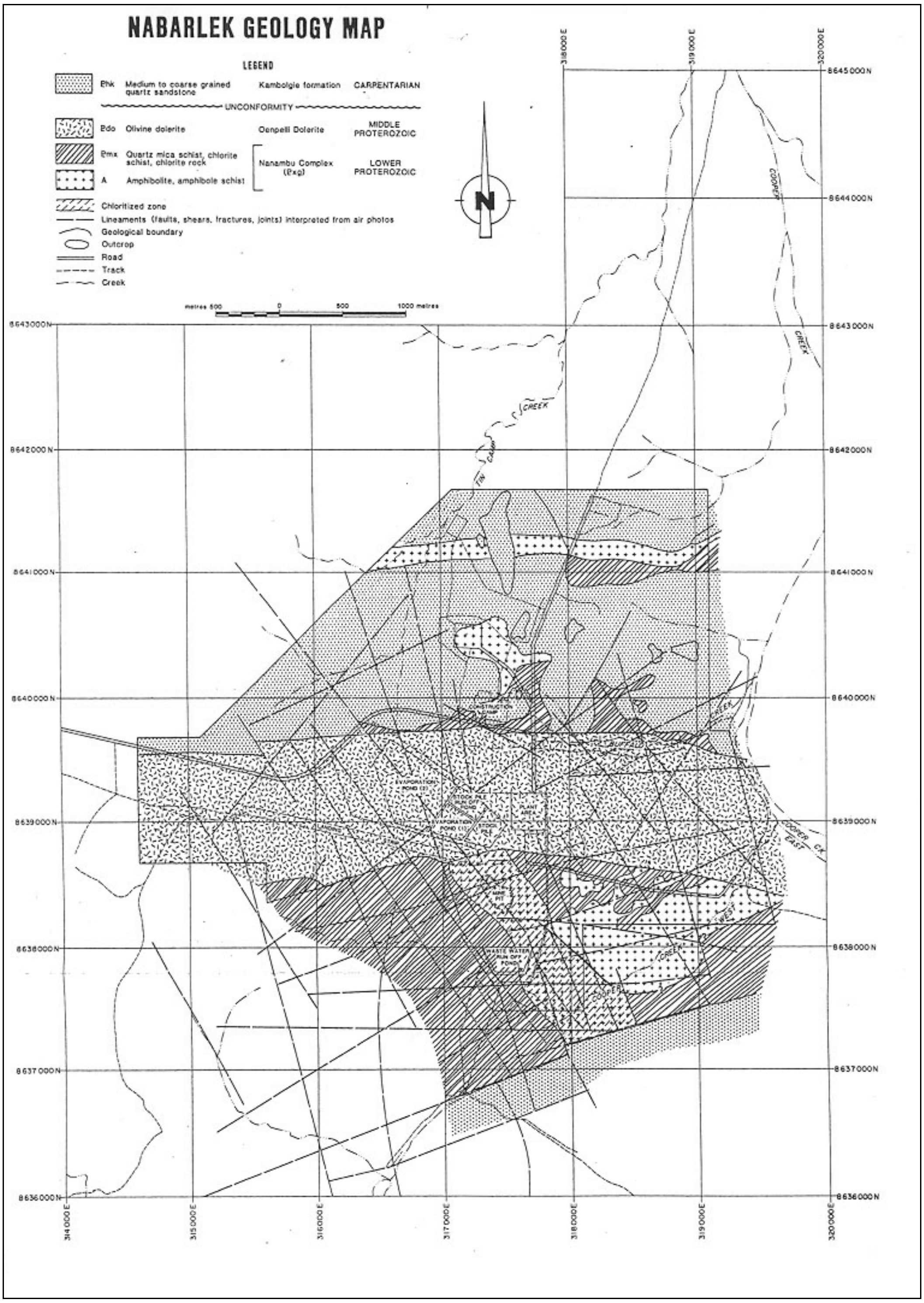


Figure 1 Geology of the Nabarlek site (Salama & Verma 1985)

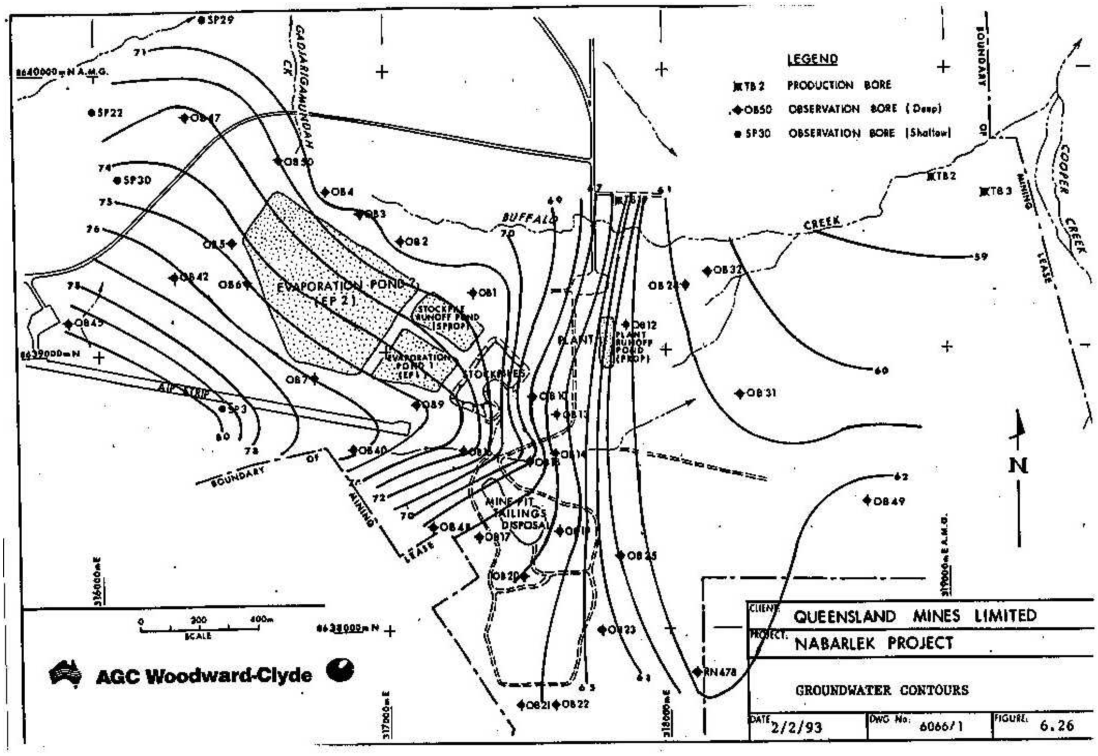


Figure 2 Groundwater contours, February 1993 (QML 1993)

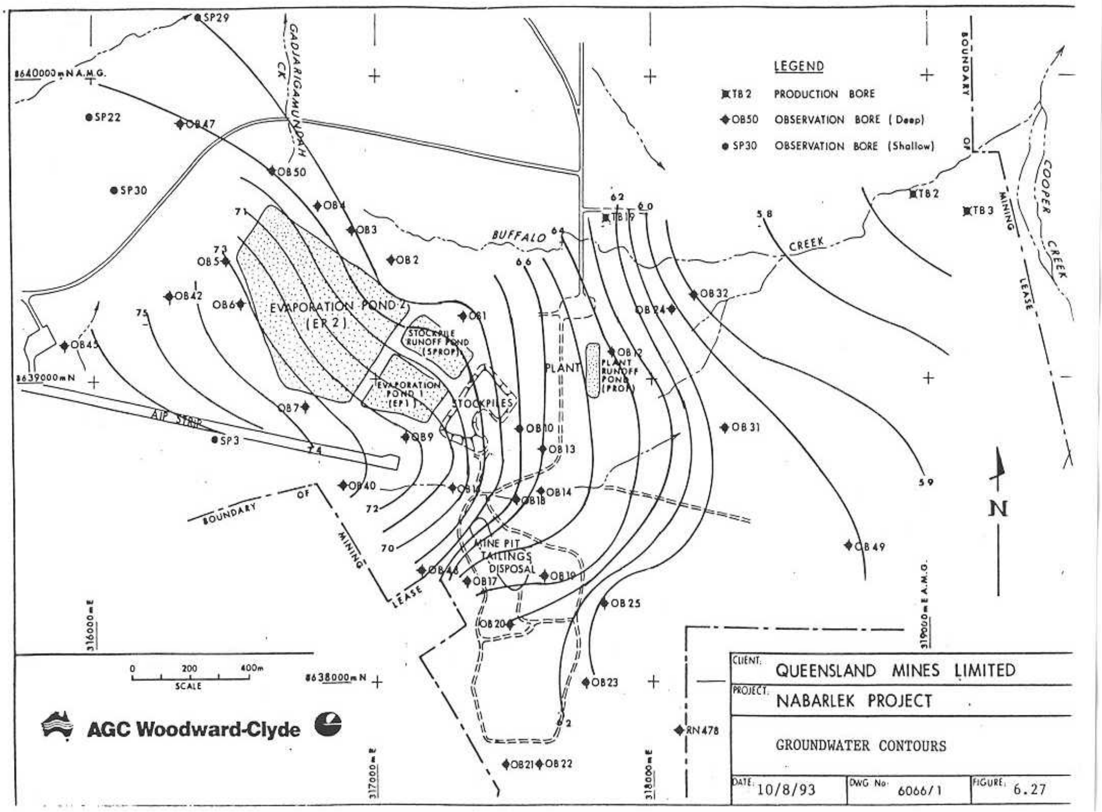


Figure 3 Groundwater contours, August 1993 (QML 1993)

Appendix B: Water quality plots and tables

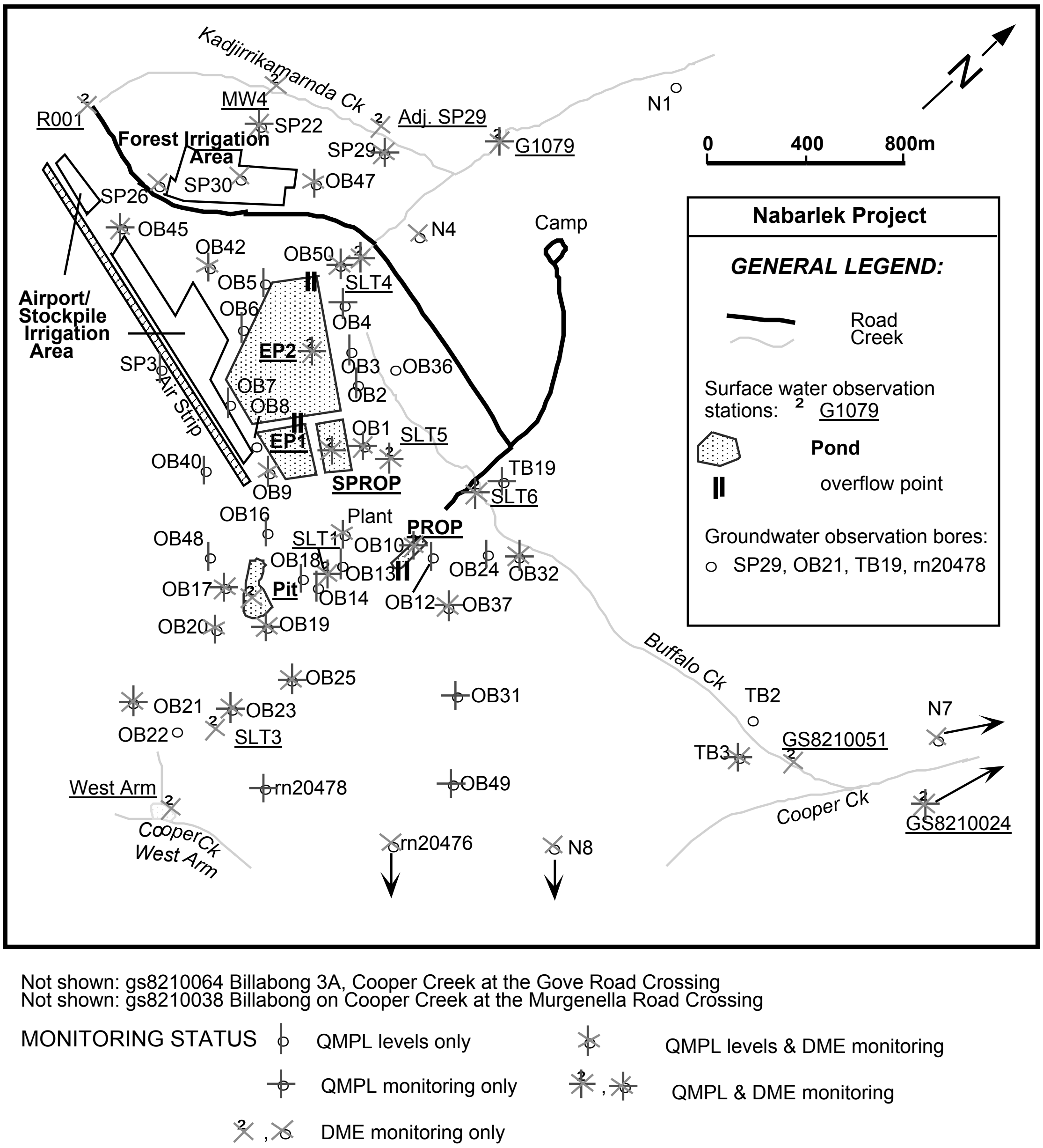
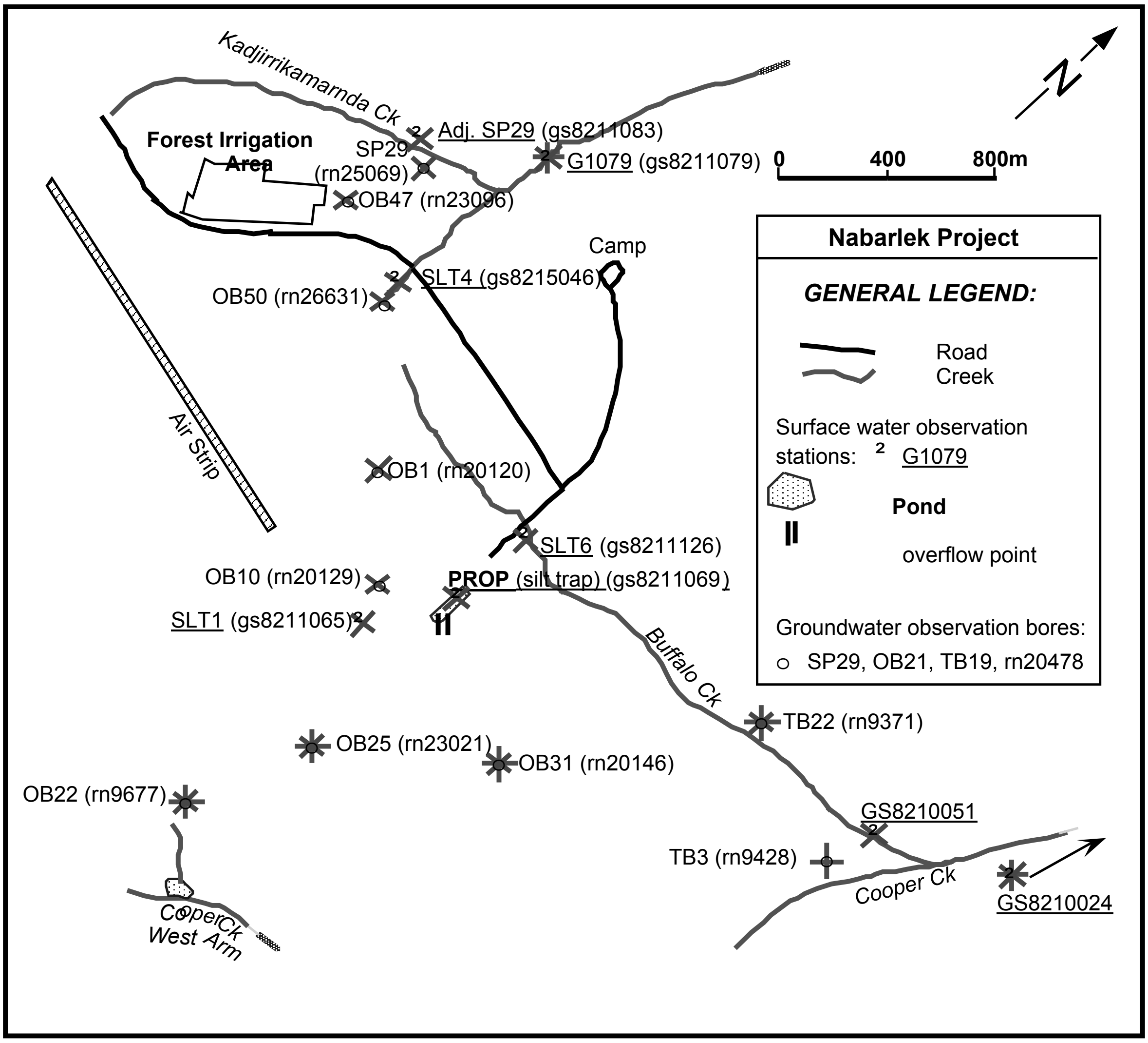


Figure 4 Monitoring program sites before decommissioning (November 1995)



Not shown: gs8210064 Billabong 3A, Cooper Creek at the Gove Road Crossing
Not shown: gs8210038 Billabong on Cooper Creek at the Murgenella Road Crossing

MONITORING STATUS — DME monitoring only; QMPL & DME monitoring; QMPL monitoring only

Figure 5 Current monitoring sites

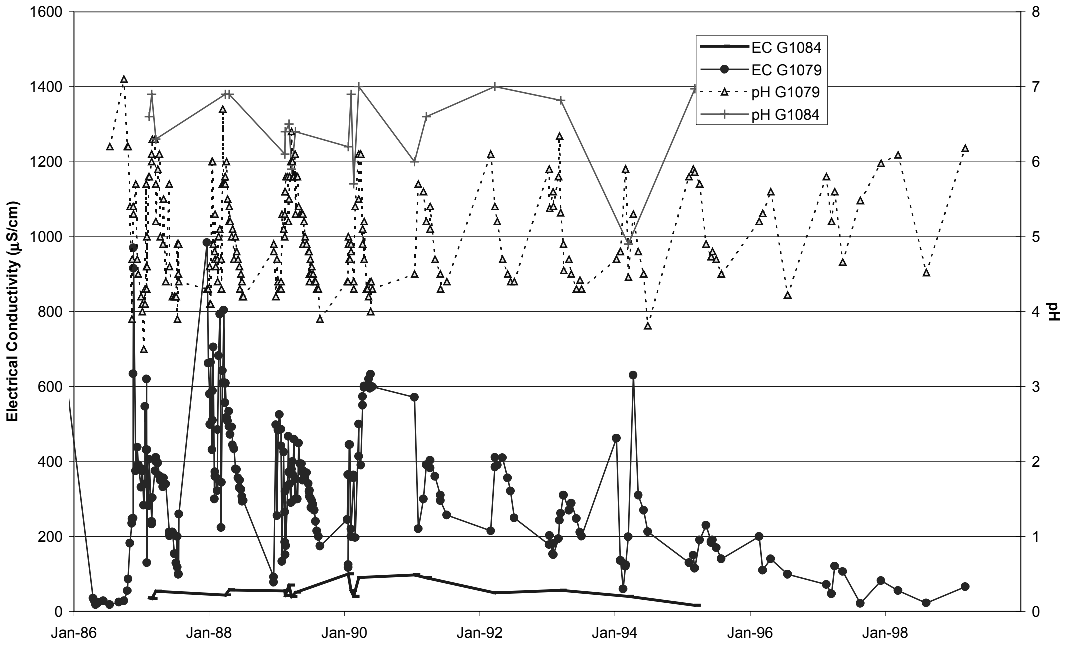


Figure 6 EC and pH at GS8211079 (downstream of the Forest Irrigation Area) and GS8211084 (Upstream of the FIA)

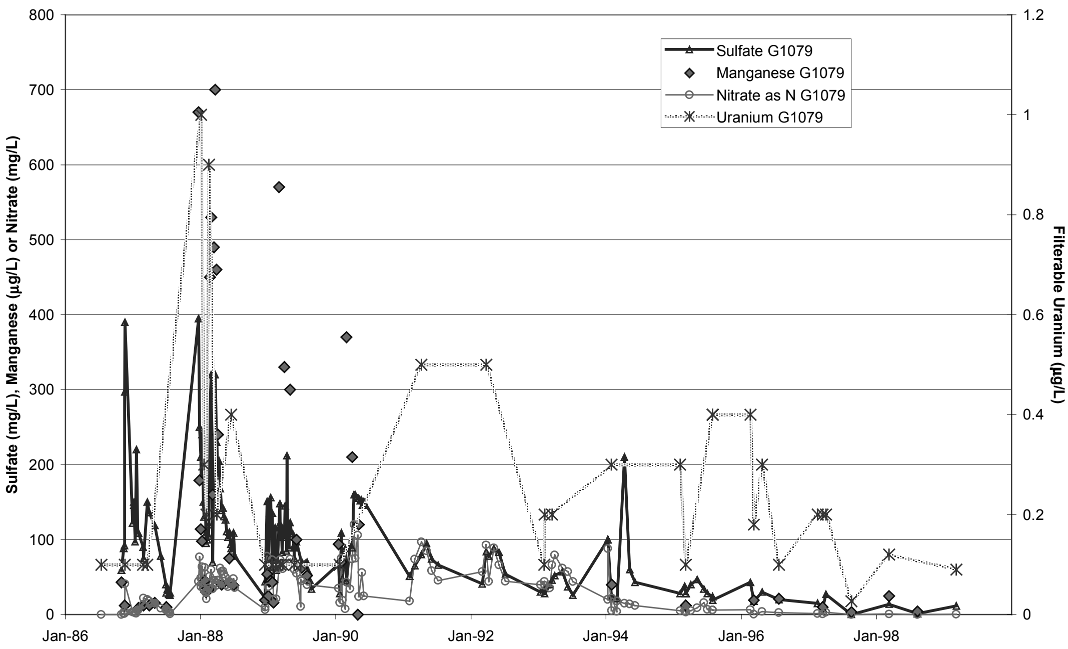


Figure 7 Sulphate, manganese, nitrate and uranium at GS8211079

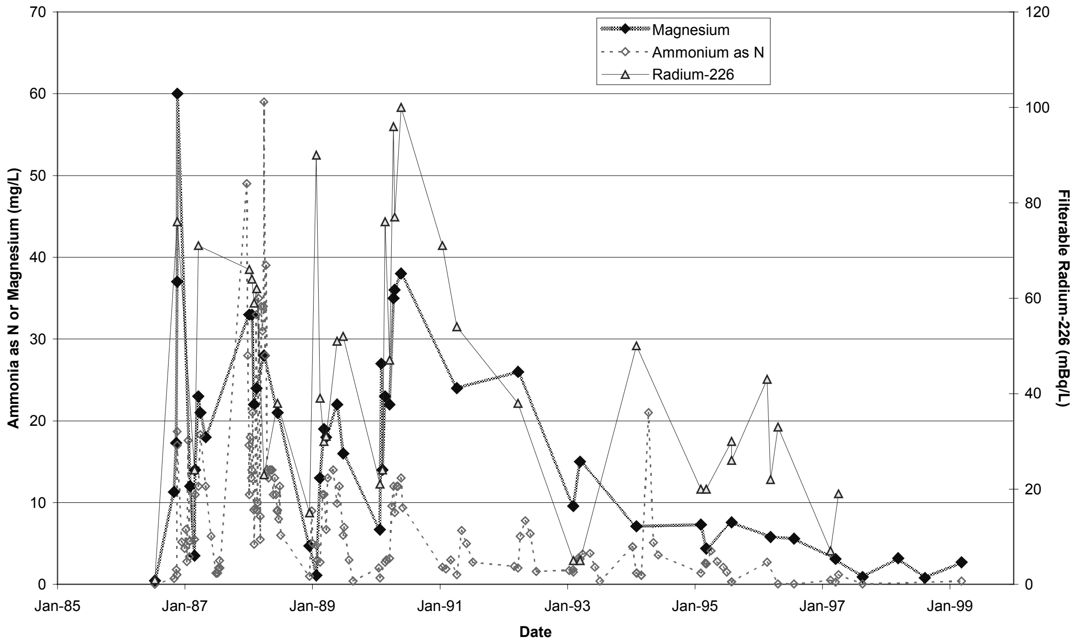


Figure 8 Magnesium, ammonium and radium-226 at GS8211079

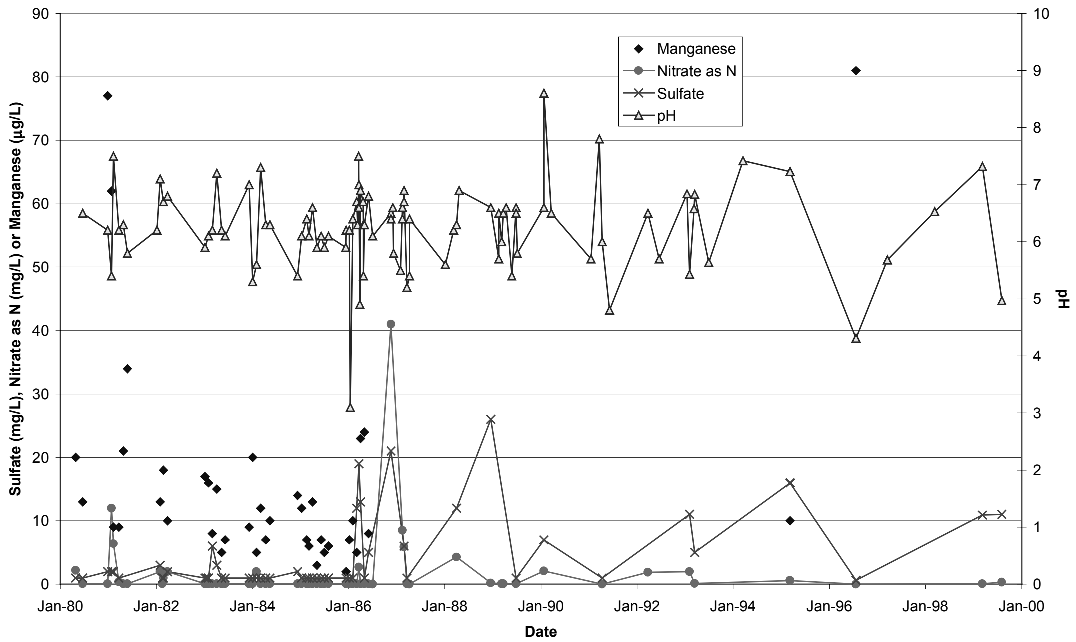


Figure 9 Sulphate, manganese, nitrate and pH at GS8210051

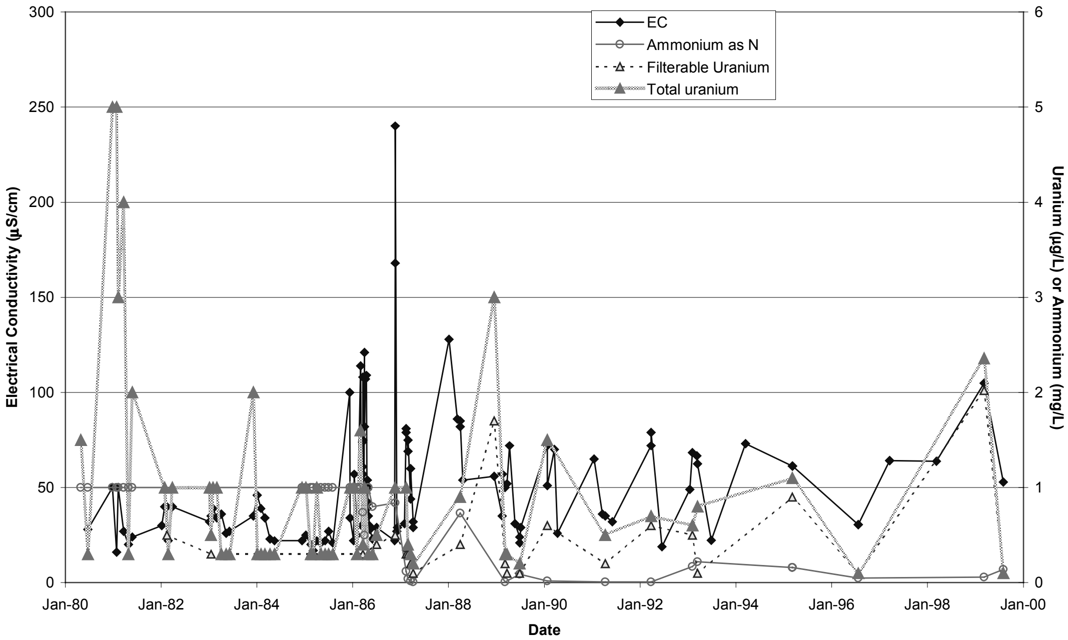


Figure 10 EC, ammonium and uranium at GS8211051

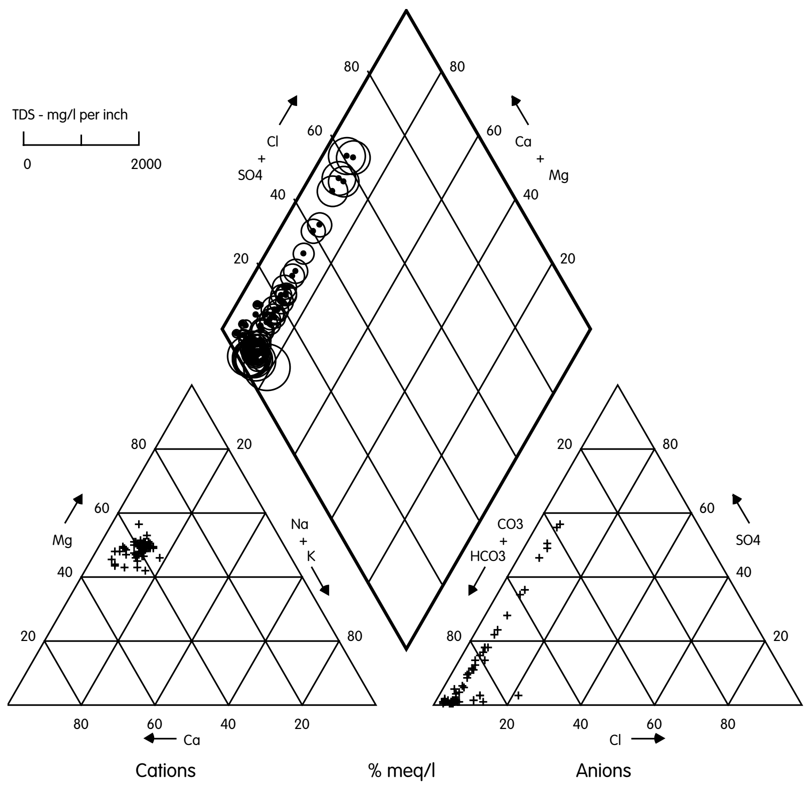


Figure 11 Piper diagram of OB31D

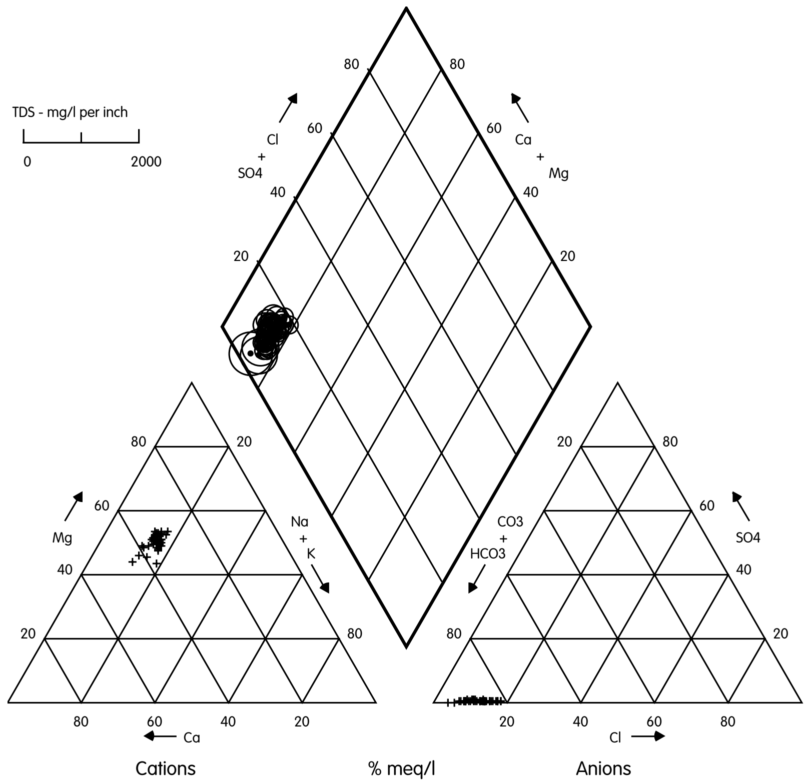


Figure 12 Piper diagram of TB22

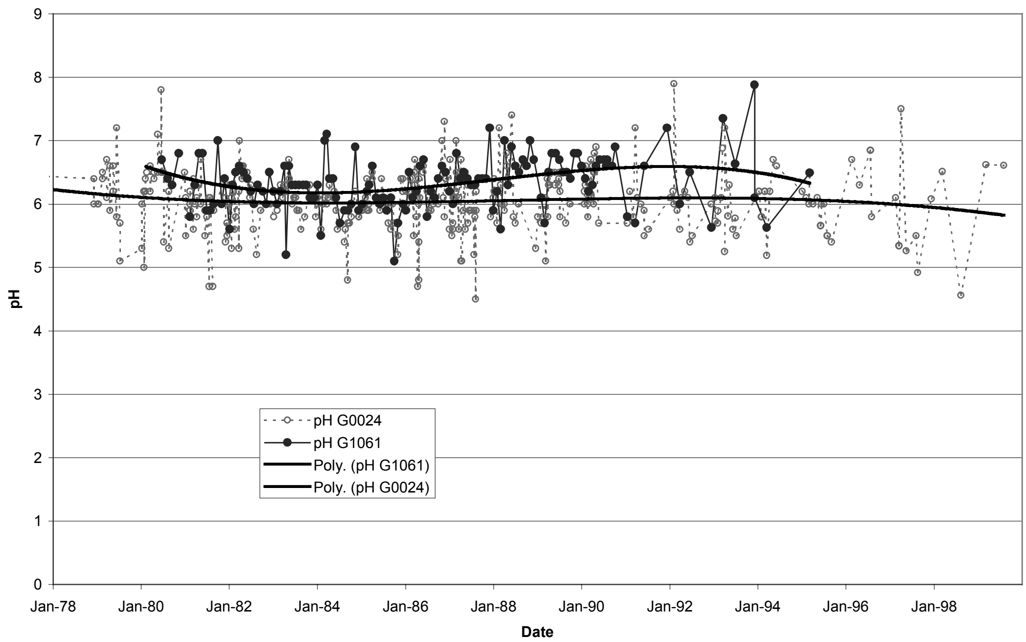


Figure 13 pH at GS8210024 (downstream Cooper Creek), and GS8211061 (upstream Cooper Creek)

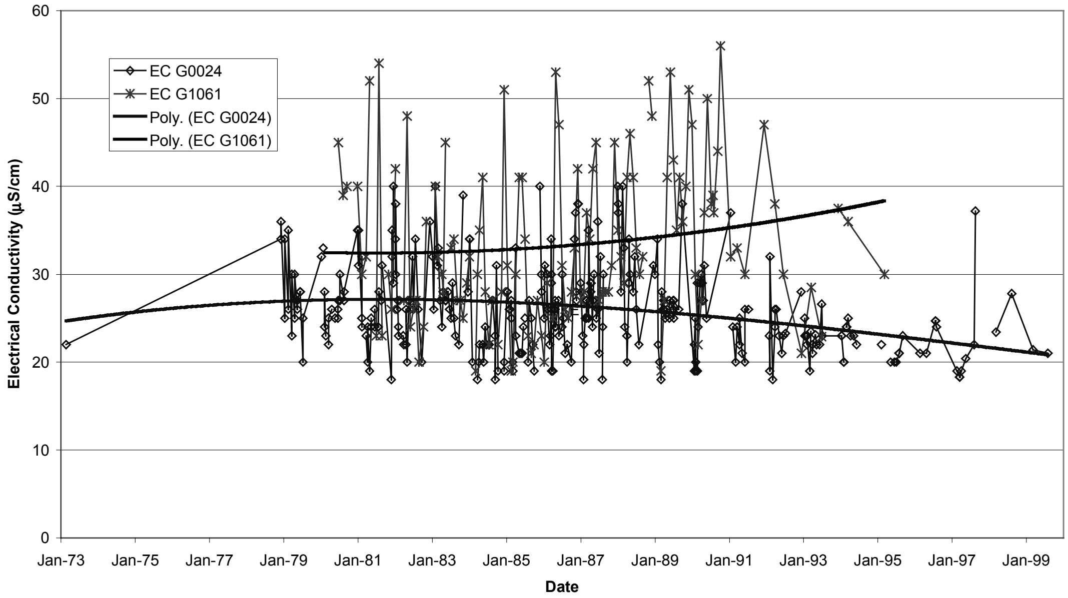


Figure 14 Electrical conductivity (µS/cm) in Cooper Creek (outliers, defined as values less than the 5%ile and greater than the 95%ile, removed)

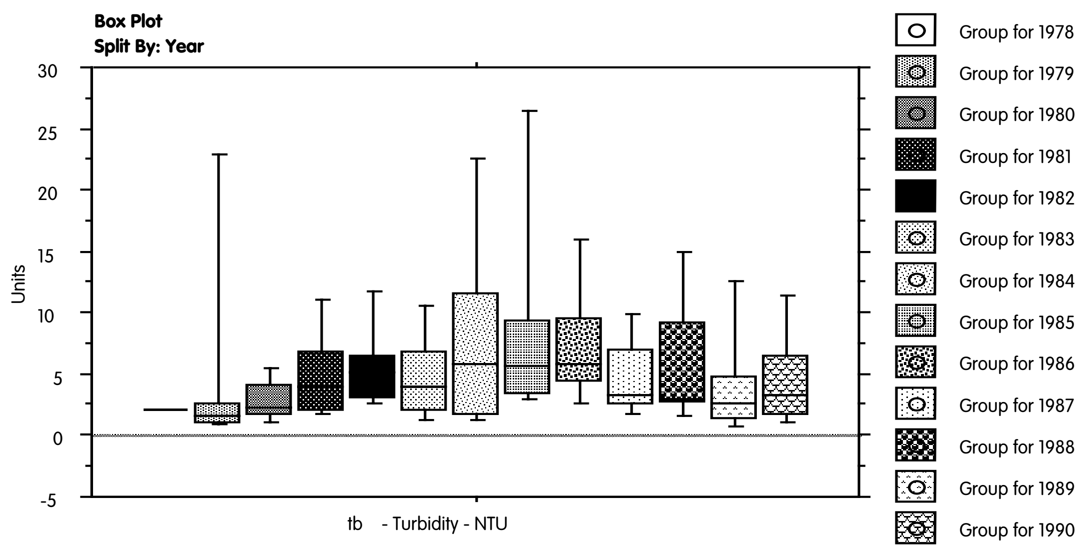


Figure 15 Box Plot of turbidity (NTU) at GS8210024

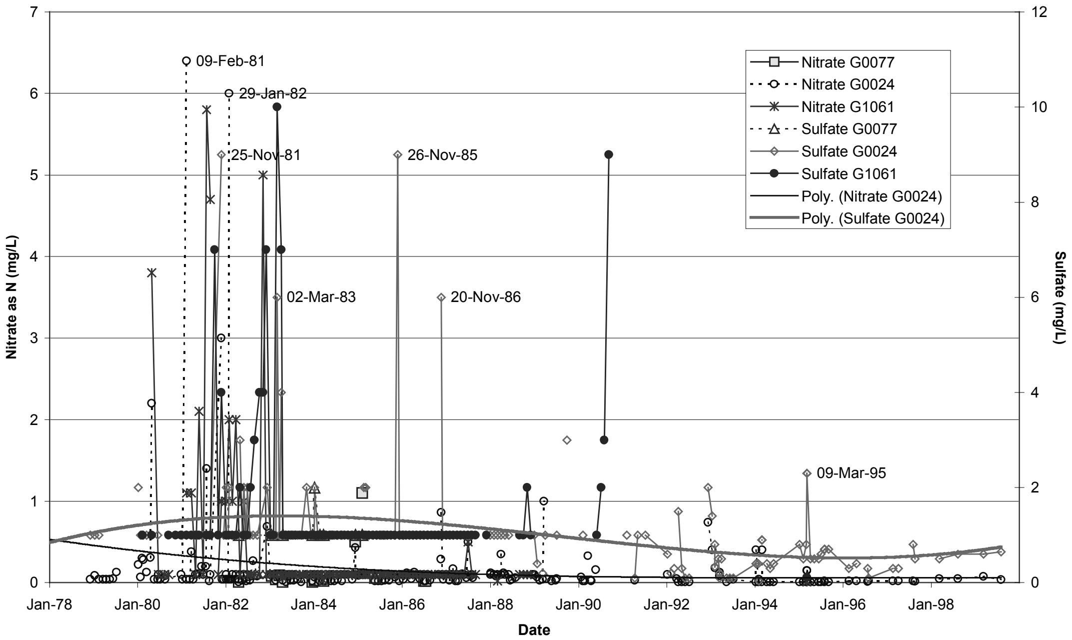


Figure 16 Sulphate and nitrate concentrations at GS8210024 and upstream (GS8210077 and GS8211061)

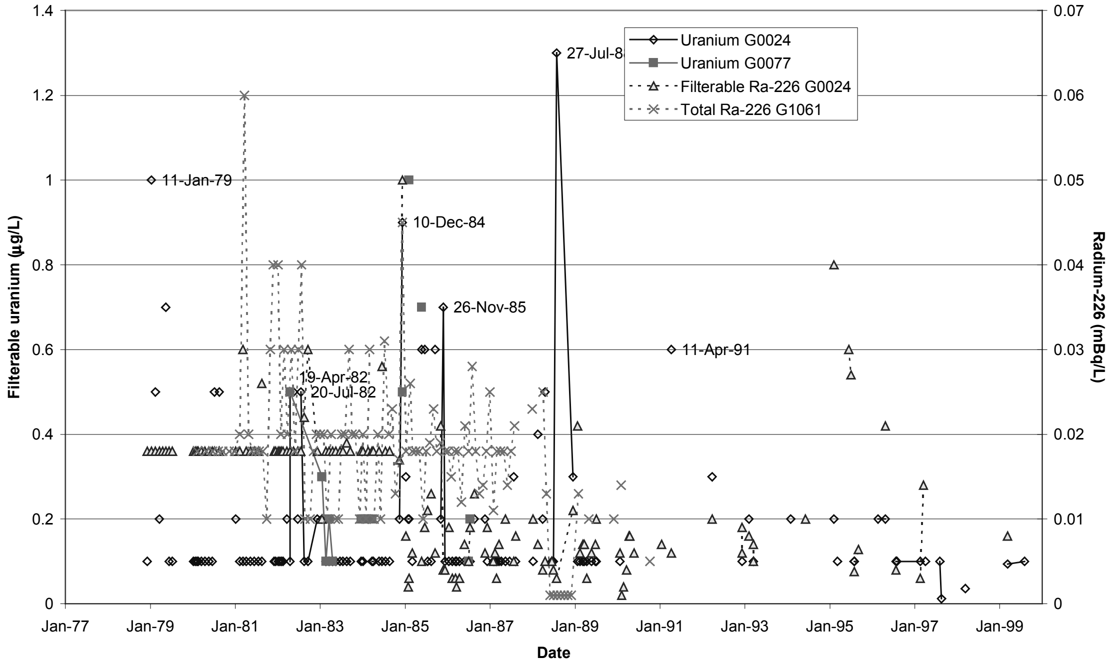


Figure 17 Filterable and uranium and ^{226}Ra in Cooper Creek

Table 2 Water quality data, March 1999

Mine	Units	ANZECC (1999) Proposed Level 1 Triggers	NHMRC Drinking Water Guidelines (1996)	QML	QML	QML	QML
Site				GS8211079	GS8210024	GS8210051	GS8211083
Sample date				9-Mar-99	9-Mar-99	9-Mar-99	9-Mar-99
E.Cond.	µS/cm			65.8	21.4	104.9	44
pH			6.5–8.5#	6.18	6.62	7.32	6.04
HCO_3	mg/L			21.942	7.314	27.4275	7.314
Na	mg/L		180#	2.5	1.8	3.3	1.9
K	mg/L			0.3	0.2	0.4	0.1
Mg	mg/L			2.7	0.9	5.1	1.8
Ca	mg/L			2.2	0.6	8.5	1.3
Cl	mg/L		250#	2.3	3	3.8	1.9
NO_3-N	mg/L	0.027	11.3	0.48	0.07	<0.05	0.38
NO_2-NO_2	mg/L		3	<0.16	<0.16	<0.16	<0.16
NH_4-N	mg/L	0.026	0.39#	0.41	<0.06	<0.06	0.31
SO_4	mg/L		250#	11.7	0.6	10.9	7.6
SiO_2	mg/L			8.4	5.9	7.6	7.3
B	µg/L	4.8	300	9.5	10.9	8.5	22.4
Al(f)	µg/L			57.94	56.85	49.11	79.76
Al(t)	µg/L	1.2	200#	88.30	291.37	61.57	83.16
V	µg/L	6*		0.49	0.92	0.89	0.45
Cr	µg/L	1.1	50	<0.1	0.3	<0.1	0.2
Mn(f)	µg/L			8.35	3.35	10.26	7.66
Mn(t)	µg/L	47*	100#	8.74	4.95	12.62	7.68
Fe	µg/L		300#	267	428	432	360
Co	µg/L	0.24		0.37	0.17	0.15	0.32
Ni	µg/L	0.7	20	0.25	0.24	0.32	0.26
Cu	µg/L	0.33	2000	0.29	1.04	0.45	0.19
Zn	µg/L	2.4	3000#	1.8	<0.1	0.4	<0.1
As	µg/L	7	7	0.44	0.11	0.14	0.65
Se	µg/L	1.4	10	<0.2	<0.2	<0.2	<0.2
Mo	µg/L	6.7*	50	0.02	0.06	0.04	0.05
Ag	µg/L	0.005	100	<0.01	0.1	<0.01	0.03
Cd	µg/L	0.013	2	0.08	0.03	<0.02	0.03
Sb	µg/L	7.6*	3	<0.01	<0.01	<0.01	<0.01
Hg	µg/L	0.013	1	<0.02	<0.02	<0.02	<0.02
Tl	µg/L	21*		<0.01	<0.01	<0.01	<0.01
Pb	µg/L	1.2	10	0.4	0.1	<0.01	0.12
U(f)	µg/L			0.090	0.094	2.020	0.029
U(t)	µg/L	2.4		0.123	0.273	2.358	0.061

* Triggers are not Level 1 triggers (either Level 2 or interim). # Values are aesthetic. Values not flagged are health levels.

Note the hardness corrections for metals were not appropriate for the Nabarlek site waters which are soft waters.

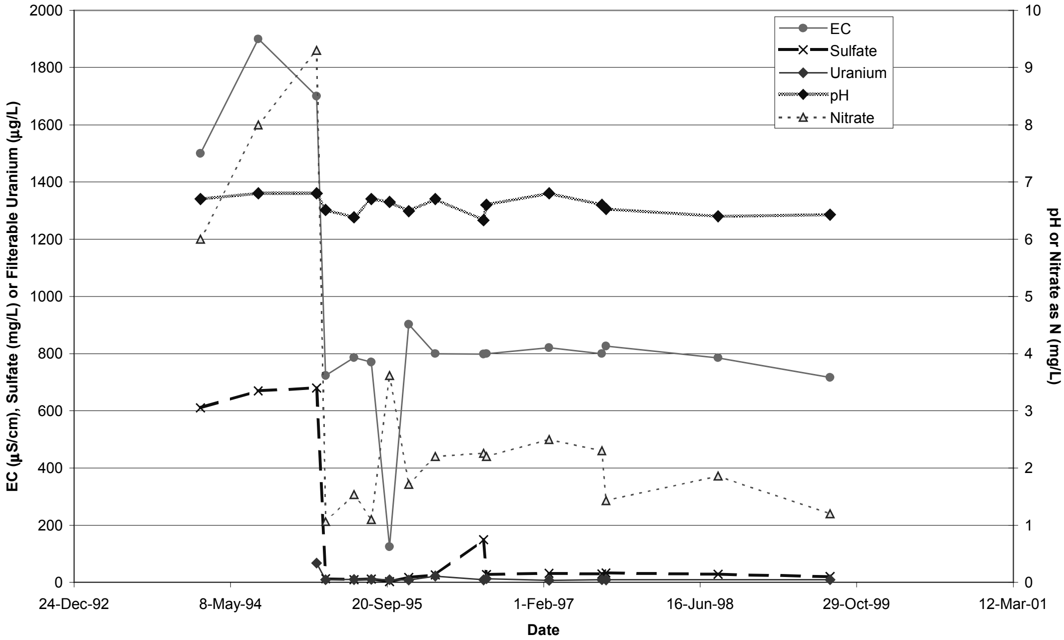


Figure 18 Decommissioning water chemistry in OB25D

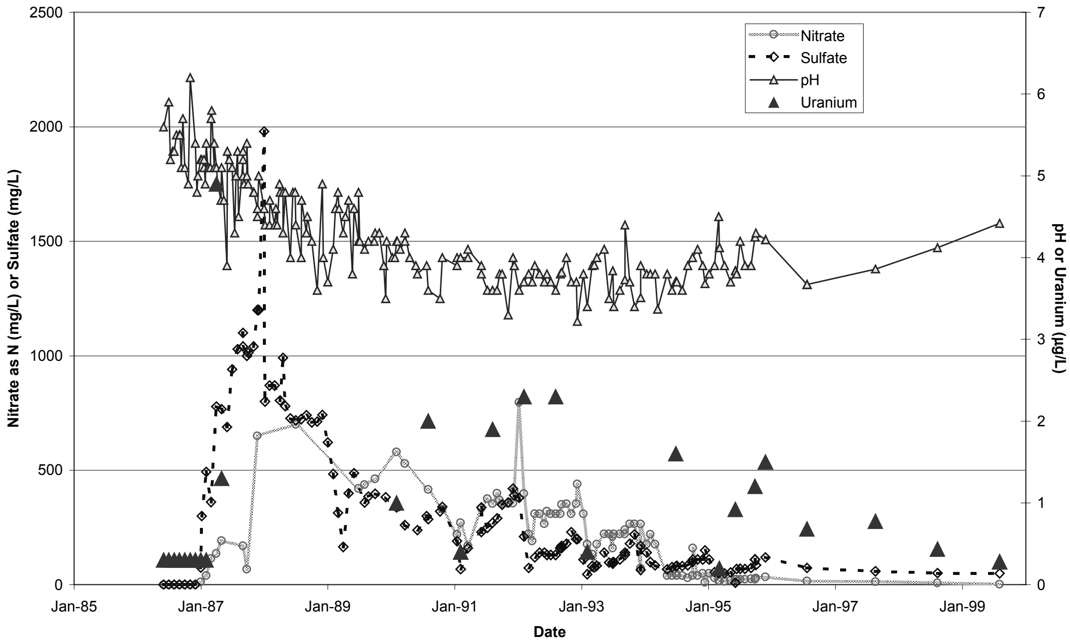


Figure 19 Nitrate, sulphate, pH and uranium in SP29 (shallow bore downgradient of the former FIA)

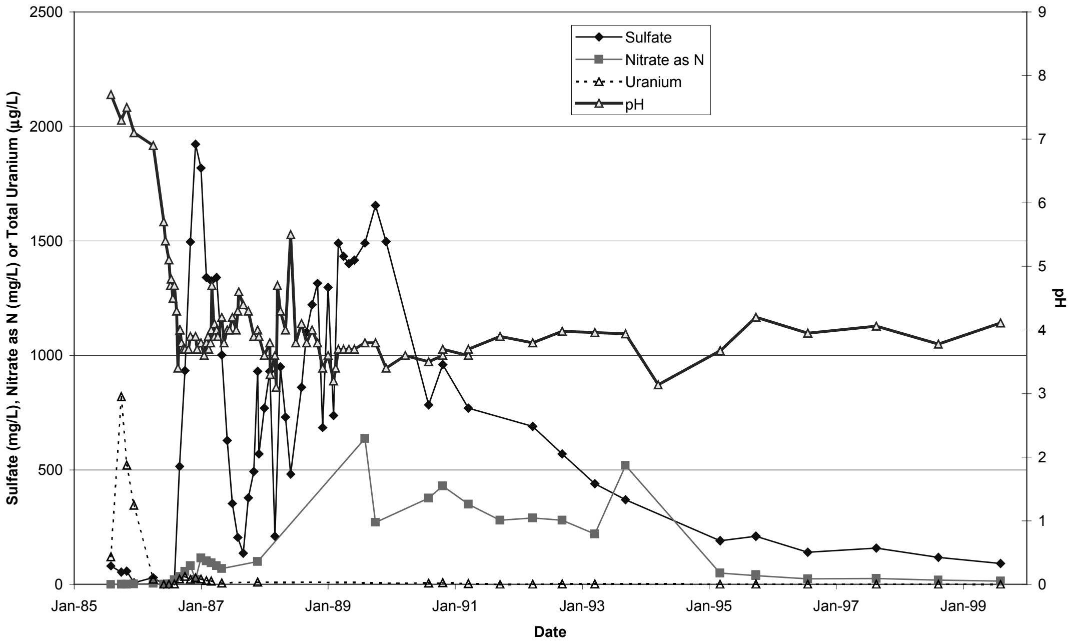


Figure 20 Nitrate, sulphate, pH and uranium in OB47D (deep bore downgradient of the former FIA)

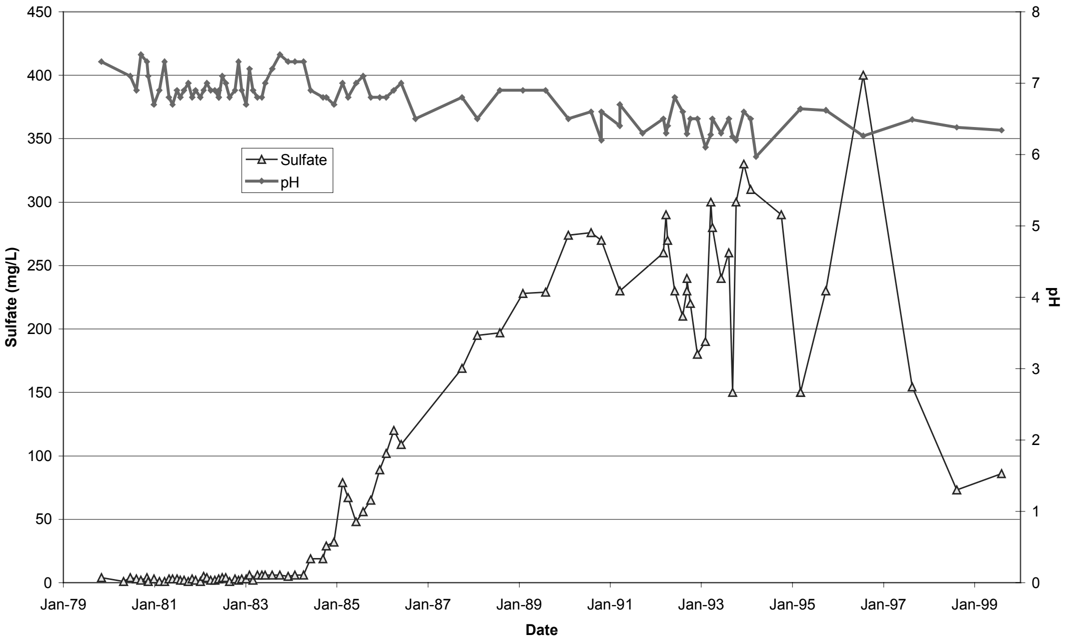


Figure 21 pH and sulphate in OB10D

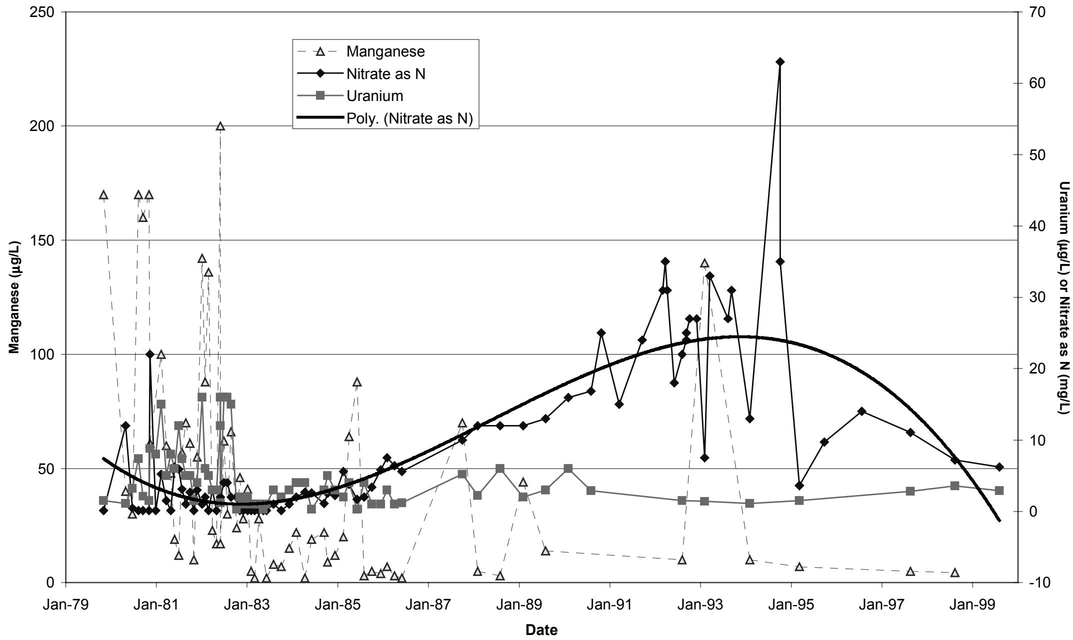


Figure 22 Manganese, nitrate and uranium, OB10D

Table 3 Ground water quality, August 1999

Sample #	Units	NHMRC Drinking Water Guidelines (1996)	99.0462	99.0468	99.0470	99.0471	99.0472	99.0473	99.0474	99.0476	99.0477	99.0479
Site Name			OB1D	OB31D	OB21	OB25D	TB2	TB22	OB19	OB10D	SP29	OB47
gs/rn			rn20120	rn20146	rn9676	rn23021	rn9427	rn26631	rn9674	rn20129	rn25069	rn23096
Mine Code			QML	QML	QML	QML	QML	QML	QML	QML	QML	QML
Sample Date			5-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	5-Aug-99	5-Aug-99
pH		6.5–8.5*	6.43	6.91	6.78	6.43	7.2	7.34	6.54	6.34	4.42	4.11
E. Cond.	µS/cm	750*	784	1058	375	717	364	517	992	674	133.4	362
Temp.	°C		31.9	32.3	21.2	33.6	32.1	32.3	33	32	31	32
HCO_2	mg/L		49.4	274	158	166	154	256	366	293	0	0
Eh	mV		281	322	123	318	302	80	298	300	489	544
Na	mg/L	180*	24	75	7.8	8.2	11	15	24	18	1.6	3.2
K	mg/L		0.25	0.65	0.93	1.6	0.63	0.5	1.3	0.66	0.42	1.7
Mg	mg/L		42	66	43	78	29	38	120	50	7	10
Ca	mg/L		74	57	7.2	16	21	36	2.8	50	6.4	9.6
Cl	mg/L	250*	16	96	15	120	6.9	16	170	32	2.5	5.4
NO_3-N	mg/L	11.3	3.2	1.2	<0.005	1.2	0.043	<0.005	<0.005	6.2	2	14
NO_2-N	mg/L	3	0.006	0.049	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
NH_4-N	mg/L	0.39*	<0.005	0.03	0.09	<0.005	0.02	0.01	7.1	<0.005	0.02	21
SO_4	mg/L	500	420	166	1	20	<0.1	0.51	23	86	49	92
SiO_2	mg/L		72	79	32	32	41	39	24	75	19	11
Al(f)	µg/L		<5	6.8	<5	<5	<5	5.8	5.2	<5	66	130
Al(t)	µg/L	200*	<5	31	10	20	6.4	14	14	11	100	130

Table 3 continued

Sample #	Units	NHMRC Drinking Water Guidelines (1996)	99.0462	99.0468	99.0470	99.0471	99.0472	99.0473	99.0474	99.0476	99.0477	99.0479
Site Name			OB1D	OB31D	OB21	OB25D	TB2	TB22	OB19	OB10D	SP29	OB47
gs/rn			rn20120	rn20146	rn9676	rn23021	rn9427	rn26631	rn9674	rn20129	rn25069	rn23096
Mine Code			QML	QML	QML	QML	QML	QML	QML	QML	QML	QML
Sample Date			5-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	5-Aug-99	5-Aug-99
Li	µg/L		8.28	29.4	51.36	100.90	49.12	2.05	105.30	26.52	1.62	4.31
Be	µg/L		<0.05	<0.1	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.22	0.22
B	µg/L	300	3.6	11	17.9	13.7	14.5	15.7	28.7	22.0	22.0	23.0
Sc	µg/L		19.8	25	7.8	7.9	9.1	10.7	6.3	20.8	4.6	3.1
Ti	µg/L		12	16	5	5	6	6	5	12	3	<2
V	µg/L		20.39	31.1	0.45	13.23	15.80	12.36	2.10	30.28	0.23	0.22
Cr	µg/L	50	0.2	0.5	<0.1	0.2	<0.1	<0.1	0.5	1.5	0.1	<0.1
Mn	µg/L	500	419	176	168	6.40	1.05	322	556	18.5	90.2	142
Fe(f)	µg/L		28	<5	2300	<5	<5	19	920	9.7	240	73
Fe(t)	µg/L	300*	240	36	3900	<5	<5	25	990	38	450	77
Co	µg/L		2.57	0.71	0.44	0.12	0.05	0.72	0.48	0.29	1.70	0.56
Ni	µg/L	20	0.45	0.09	0.36	0.09	<0.01	0.92	0.37	0.23	0.83	1.01
Cu	µg/L	2000	1.40	5.16	0.39	1.44	0.60	0.80	0.53	0.68	10.25	31.70
Zn	µg/L	3000*	57.6	53.2	38.7	62.4	10.1	20.4	42.1	41.8	9.2	49.0
As	µg/L		0.35	1.7	0.22	0.11	0.08	<0.05	0.37	0.82	<0.05	<0.05
Se	µg/L	10	0.8	1.7	0.3	0.7	0.3	0.4	1.3	0.7	<0.2	1.1
Br	µg/L		46	220	53	86	12	62	232	82	11	35

Table 3 continued

Sample #	Units	NHMRC Drinking Water Guidelines (1996)	99.0462	99.0468	99.0470	99.0471	99.0472	99.0473	99.0474	99.0476	99.0477	99.0479
Site Name			OB1D	OB31D	OB21	OB25D	TB2	TB22	OB19	OB10D	SP29	OB47
gs/rn			rn20120	rn20146	rn9676	rn23021	rn9427	rn26631	rn9674	rn20129	rn25069	rn23096
Mine Code			QML	QML	QML	QML	QML	QML	QML	QML	QML	QML
Sample Date			5-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	4-Aug-99	5-Aug-99	5-Aug-99
Sr	µg/L		649.17	435.54	33.48	60.27	267.97	276.07	16.36	341.77	48.68	54.67
Mo	µg/L	50	0.11	0.17	0.93	0.02	0.04	0.04	0.24	0.04	<0.01	<0.01
Ag	µg/L	100	0.06	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cd	µg/L		0.20	0.16	0.05	0.10	0.02	<0.02	0.06	0.11	0.09	0.33
Sb	µg/L		0.03	0.15	0.05	0.02	<0.01	<0.01	0.03	<0.01	<0.01	0.03
Ba	µg/L		47.87	101.88	14.13	17.27	107.60	40.52	122.50	103.90	76.52	49.21
Pt	µg/L		<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Au	µg/L		<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Hg	µg/L	1	<0.02	<0.05	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Tl	µg/L		<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.07
Pb	µg/L	10	0.79	3.51	0.40	0.31	<0.01	1.76	0.49	0.84	0.86	1.75
Bi	µg/L		0.03	0.17	0.04	0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
U(f)	µg/L		<0.1	3.9	0.11	9.3	1.1	0.88	1.7	2.7	0.22	0.34
U(t)	µg/L	20	<0.1	3.7	0.13	76	1.2	0.83	1.9	2.9	0.28	0.35

* Guideline for aesthetics. Non-flagged numbers refer to guidelines for health.

Monitoring indicators of minesite rehabilitation success

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Introduction

The objectives of rehabilitation in mined lands have been broadly agreed for some time, but comprise vague statements about stability to erosion and return of productivity (Bell 1986, 1990). In recent times there has been a shift in the end use of rehabilitated mine lands from agricultural production to natural ecosystems as the desired final form of rehabilitation. As a consequence, the methods by which satisfactory rehabilitation might be judged changed from those relating to productivity and farming management practices (such as supplying deficient resources like water and fertiliser) to those concerned with self-sustainable ecosystems with little or no management inputs (Mulligan & Bell 1991). Natural ecosystems are inherently more complex than managed landscapes as there are often numerous subtle pathways for the maintenance of processes such as nutrient cycling, infiltration, bioturbation and seedling germination.

We have alluded to what we call the 'agronomic engineering' mindset in early rehabilitation (CSIRO 1996). Holling and Meefe (1996) also call this 'command and control'. The expectation of this mindset is that the system is constantly managed and adjusted to achieve desired outcomes. This is probably justified when lands are to be used for agricultural production, though Williams (1999) has suggested that Australian agriculture needs to emulate nature to be sustainable in the long term.

Assessment of the status of natural ecosystems has also had a chequered past in Australia, where, during the 1980s, US models based on plant succession to a single climax composition were rejected (Wilson 1984) in favour of notions of multiple stable states and transitions between them (Westoby et al 1989). The concepts of resilience were introduced and developed slowly, reflecting something of a disconnection between theory and application of ecological principles. Many early attempts to devise monitoring procedures used sophisticated data analysis reflecting mental models that scientists use in communicating between members of their peers (eg Hacker 1984). Suspicions that 'revegetation but not restoration' has occurred have been levelled but were hard to substantiate (Mentis & Ellery 1994).

Some criteria for rehabilitation success seem to imply that a static 'desirable' biotic composition for both flora and fauna is an appropriate model to follow. This does not allow evolutionary succession or change to be accommodated, or recognise that considerable spatial and temporal heterogeneity exists in natural ecosystems. Prescribed species composition and erosion rates are superficially clear-cut and simple to apply, but can lead to confusion and confrontation. It is unlikely that we will ever have sufficient knowledge about any ecosystems or landscapes to have the degree of certainty implied in list-based appraisals. These are at best, retrospective summaries and there is no explicit functional understanding, except by inference. Absence of a species is difficult to interpret.

Past monitoring procedures

Rehabilitation success has been monitored largely by following vegetation development using standard procedures in vegetation science and by measuring a number of soil properties. There are numerous references in the MCA Environmental Workshop Proceedings.[10] In particular, species composition and species lists were, and remain, a favoured way of assessing success. The plant species mix is taken to infer that underlying environmental conditions are favourable. However, absence is much more difficult to interpret. There also appears to be an expectation of species succession to a 'desired' composition, though the logic of why this should occur is obscure. Over time, emphasis has changed from a mindset of 'green and growing is good' to more specified composition characteristics, reflecting local provinance species and community composition. The role of some species as critical suppliers of ecosystem services, ie 'framework species', is growing (Reddell & Hopkins 1995). More positive measures are now being made to establish species with known functional roles early in the life of the rehabilitation (Hinz 1992). Egler (1954) anticipated this need and provided evidence of 'initial floristics' dominating 'relay floristics'.

Soil properties are quantitative and informative and particularly useful when assessing what the habitat favourability of spoil might be: whether it is too erodible, too infertile, too impermeable, too extreme a pH, etc. However, soil analyses are expensive, the data are delayed in being returned to the site and require considerable expertise to interpret. The capacity to monitor soil development dynamics is possible, but expensive (Tongway et al 1994). Mostly, they will also be site-specific in terms of numerical values, though regional or land-system data-bases could be contemplated. Achieving this on a national basis would be massively expensive and unlikely to be underwritten either by Industry or Regulators.

Whilst these procedures reflect something about a number of properties directly, and are thought to imply others, they fail to integrate a full range of ecosystem properties, so that a holistic, predictive understanding cannot be derived. The methods are generally either too slow (delayed) or too expensive to be used repeatedly to monitor status. Their use is essential in understanding basic scientific relationships, but impractical for routine monitoring. In addition, when rehabilitation is unsatisfactory in some way, lists of properties or biota have no inherent explanatory capacity by which a rehabilitation procedure can be corrected on another occasion. This leaves rehabilitation as a maze of empirical rules that might work locally but not regionally or nationally.

Ecosystem Function Analysis (EFA)

This procedure was developed originally for rangelands to overcome problems similar to those mentioned above, with a specific intention of assessing the habitat value of the soil for vascular plants of interest, for example pasture grasses. EFA was designed to ask questions of the type — *How does this system work? What goes wrong with it? How can it be rehabilitated?* In 1996–97, the rehabilitation on 13 mines was assessed with EFA procedures as a 'proof of concept' exercise (Tongway et al 1997). We applied EFA procedures on five mine types (bauxite, coal, mineral sand, iron and hard rock) in as wide a geographic spread as sponsorship permitted. We were able to show that EFA indices were able to reflect the 'trajectory of development' of the various mines. Satisfactory, doubtful and unsatisfactory scenarios were detected.

[10] MCA Proceedings: Annual Environmental Workshops. Copies held by Minerals Council of Australia (Canberra). PO Box 363, Dickson ACT 2602. Ph. (02) 6279 3600, Fax (02) 6279 3699, Email: minerals@ozemail.com.au

The approach is comprised of three modules: a conceptual framework, a field methodology and an interpretational framework. The conceptual framework was fully explained in Ludwig and Tongway (1997, 2000), and is called ‘trigger-transfer-reserve-pulse’. This framework represents the spatial and temporal processes that regulate the manner in which vital resources are distributed, utilised and cycled in landscapes, encompassing both physical and biological interactions. The basic unit of observation is the local watershed. It is a ‘systems’ approach to understanding landscapes, rather than a ‘list of biota and list of properties’ approach. It is explicitly dynamic and spatial, focusing on processes rather than on objects or properties alone. Feedback loops are integral and essential components.

The field methodology is comprised of a nested set of indicators reflecting both landscape scale and patch-within-landscape scale information about the status of the processes identified in the conceptual framework (Tongway 1994, Tongway & Hindley 1995, Tongway & Hindley 2000). The data are collected from a transect aligned with the direction of resource flow (ie downslope for fluvial processes and in the direction of the strongest winds in aeolian systems) and comprise a map of runoff and runon features. This is an efficient way to capture cause and effect factors.

The first data to be collected reflect ‘landscape organisation’ and identify and measure features in the landscape that regulate the flow of resources (runon zones). These may be perennial plant individuals and clumps, logs or changes in slope. These features are seperated by runoff zones where resources flow with little impediment. The sizes of these different zones form a series of indices of landscape organisation, reflecting the degree to which resources are retained in the landscape or lost.

The second set of data is at finer scale and relates to the status of processes on both the runoff and runon zones. The data are comprised of 11 simple indicators of the status of processes at the zone scale, developed over many years of observation and measurement (eg Eldridge 1991, Tongway & Smith 1989, Tongway et al 1989, Tongway & Ludwig 1994). The indicators are simple to observe in the field after appropriate training and take about 5 to 10 seconds each to evaluate by an experienced observer. Each indicator is assigned to a class reflecting differences in functional effect. The indicators are combined in several different combinations to produce indices reflecting soil stability, infiltration and nutrient cycling. Good relationships have been demonstrated between the indices and measured landscape variables (Tongway in prep, Pringle, PhD thesis 2000). Additional modules in EFA collect data on vascular plant species composition, density and size in relation to the patch types observed in the landscape transect and information about ‘habitat complexity’ an index of habitat value for fauna (Newsome & Catling 1979).

It was a design objective of EFA that it be quick and inexpensive enough to be used on a regular (eg annual) basis in order to track the progress of rehabilitation. Tongway et al (1997, fig 1) showed three examples of rehabilitation development, only one of which is satisfactory. This concept of ‘ecosystem trajectory’ lends itself to contributing to defining completion criteria, using the past record of ecosystem function. Clearly, the precision of visual estimation and classification does not compare with carefully measured conventional scientific measurements, but compensates by recognising the interaction of a number of different processes representing a wide range of physical, chemical and biological phenomena. Recent field tests have confirmed that even inexperienced observers obtain similar index data from the same field site (Tongway, unpub data). Note that the use of data from ‘analogue’ sites is integral and essential in EFA.

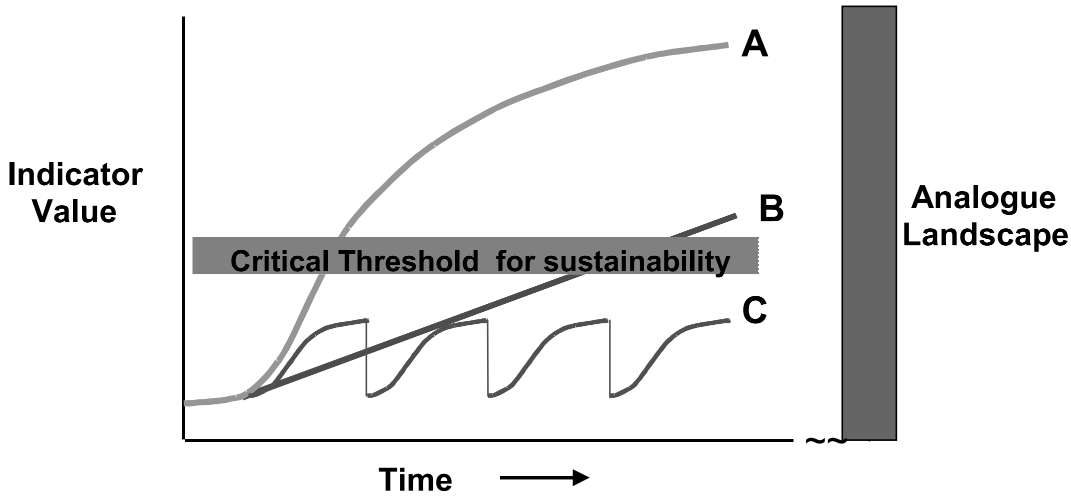

Figure 1 Three contrasting ecosystem rehabilitation trajectories

Interpretational framework

There needs to be a way of interpreting the monitoring data so that practical values and guidelines emerge that are useful in predicting success or otherwise. This is an area where relatively little work has been done at the practical level, though complex statistical models of plant species behaviour have had some attention (Friedel 1994).

Sigmoidal curves are common in biology when responses are assessed across their full range (eg the relative growth curve and population growth Krebs 1972), so there is at least a *prima facie* case to utilise this shape for interpretative purposes. The sigmoidal curve is intuitively attractive, because landscape values must have an upper and lower biogeochemical bound; the sloping line between these boundaries may vary in gradient, signifying differences in resilience. Noy-Meir (1981) utilised this form of relationship in his model of landscape structure and functioning and Bastin et al (1993) also reported a similar spatial relationship with remotely sensed grazing gradients.

Demonstration of the concept

We do not have sufficient available data in hand from minesite rehabilitation assessment to fully demonstrate the concept. Typically, a minimum of 6 time-series points with 2 of those representing initial and final values respectively would be needed as a minimum. The predictions of final values and ecosystem success improve as more data is included in the analysis.

The concept is demonstrated here using data collected in a chenopod shrubland in South Australia (Tongway & Hindley 1999). As depicted (fig 2), this resembles the shape of a rehabilitation trajectory over time, for a minesite (fig 1). The landscape unit under study was a flat to gently undulating landform, with a calcareous shallow loam soil, underlain by calcrete at shallow depths. 'Distance from water' is the surrogate, in this instance, for a gradient in stress and/or disturbance and plotted here as the logarithm. The y-axis is a soil stability index derived from the EFA methodology.

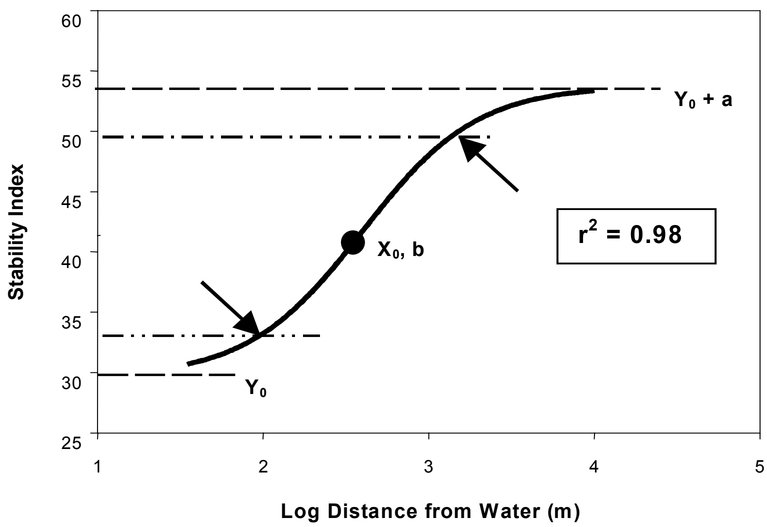

Figure 2 Depicts a fitted 4-parameter sigmoid relationship of the form $y = y_o + (a/[1 + exp^{-\{t - to/b\}}])$. The y-axis represents an indicator of landscape function (soil stability in this case). (y_o+a) represents the value of the upper asymptote, y_o the computed value of the lower asymptote, x_o represents the location of the inflection point of the curve on the x-axis and b the gradient at the inflection point. In this example a = 24.17, b = 0.346, x_0 = 2.6, y_0 = 29.61.

The curve parameters represent values related to functional response of the landscape to stress and disturbance: how stable it can be when fully functional and how unstable when severely stressed. The dynamics of 'functional' response in this case are due to the nature of the soil type and its moderate capacity to resist erosion.

- The point X_0 is the inflexion point of the curve representing the threshold when the ecosystem begins to 'plateau out' or reach its biogeochemical potential.
- The slope b on minesites represents the rate of increase of the assessed index over time. High values represent quickly responding ecosystems; low values denote slow response.

The location of the points of maximum curvature (arrows) could be used as threshold values. The upper point could be used to differentiate between self-sustaining landscapes and those that are under threat of accelerated erosion or some other form of diminished function. In figure 2, those parts of the rangeland paddock greater than about 1 km from water are self-sustaining.

This curve can be fitted and values for each of the curve parameters calculated by commercial software packages. The points of maximum curvature represent landscape threshold values for management and can be determined easily from the curve plot. The four curve parameters can be used to characterise the functional response of different landscape types, whilst the current location of the site on the curve can be used to predict its future in specified scenarios.

In the minesite rehabilitation scenario, y_0 represents the functional status at time zero. As data from periodic monitoring accumulates, they can be fitted to a sigmoidal curve, so that the values of x_0 and b are evaluated. b (the slope at the inflexion point) is an important development factor, and should show a steep response over time. In early years, predicted value of (y_0 + a) should be ignored, as it will be highly inaccurate, but over time, this value will assume greater importance. Plateauing of the upper curve at low values or at an early stage would constitute warning signals. Target values of (y_0 + a) would be derived from analogue sites, *but must be used with caution*. Each of the indices needs to be fitted to an individual sigmoidal curve, thus generating a family of curves at both site and patch scale. If sites have been well prepared, stability might well have a high initial value and not change much, however, nutrient cycling would necessarily start with low values, but increase steeply over time.

EFA does not deal with issue such as weeds in other than a functional sense. The role of weeds in regulating flowing resources would be assessed on face value. 'Weediness' involves values that do not map onto function. Weed 'values' can be derived and used in their traditional manner. EFA might be used to examine whether mine landform development favoured the establishment of weeds and the failure of desired species in an intensive but local analysis. Erosion features with spatial continuity, such as rills are also dealt with by a sub-routine of landscape organisation.

Summary

EFA is conceived as an inclusive monitoring procedure, inexpensive enough in deployment to use at regular intervals, but intrinsically integrated to reflect a wide range of physical, chemical and biological processes. Ecosystem development trajectories are the expected medium to assess progress. These can be related to species composition and growth rates of vascular plants and to the development of ecological niches for fauna. Being based on indicators, it is amenable for use by non-specialists. In practice it gives consistent results between observers and the information derived used to assist the process of satisfying completion criteria.

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Termites as ecological indicators of mine-land rehabilitation in tropical Australia[11]

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Abstract

This paper presents examples from field research of termites as indicators of rehabilitation success in the wet–dry tropics at Nabalco's bauxite mine, Gove, Australia and in Sierra Leone, West Africa.

Field studies indicate that soil-plant-animal interactions are crucial in determining the recovery of disturbed land and that termites play an over-riding role in the process. Termites are seen as ecological indicators for successful soil and vegetation development in humid tropical environments.

In land rehabilitation, termites help to create healthy, self-regulated vegetation systems that integrate with the surrounding landscapes and build structures and functions equal to those of the pre-disturbed system. They are reliable in signaling the health and stress factors of a system and provide a predictable response.

1 Introduction

Termites are recognised as useful ecological indicators of successful soil and vegetation development on reclaimed mined land. They are one of the most active organisms in many tropical and sub-tropical soils, consuming large quantities of organic matter, probably more than any other group. For example, Wood and Sands (1978) point out that termites have

> a profound effect on redistribution of soil particles, on physical and chemical properties of soil and consequently on vegetation.

The importance of termites in soil development has long been known and they have been described as the tropical analogue of the earthworm (Drummond 1888). They successfully modify the soil profile by moving soil from various horizons and bringing it to the surface in the form of sheets, linings between leaf litter and on the bark of shrubs and trees, and mounds.

The activity of termites in mined land rehabilitation after bauxite mining at Gove has been described by Reddell et al (1992) and at Weipa by Spain (pers comm). The aim of this paper is to promote interest and awareness of the importance these social insects have in the rehabilitation of disturbed land.

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[11] Observations from twenty-eight years of rehabilitation experience at the Gove bauxite mine in northern Australia and in Sierra Leone (West Africa)

2 Rehabilitation

The first studies for Nabalco Pty Limited, on termite activity of rehabilitated mined site at Gove, were carried out in 1992/93 by the CSIRO Mine-Site Rehabilitation Research Group. Results were compared with data collected from Sieromco's bauxite mine in Sierra Leone, West Africa, where mined land in the hill regions was being rehabilitated to indigenous forest vegetation with interplanting of economic species.

The requirements of land rehabilitation after bauxite mining by Nabalco at Gove, north-eastern Arnhem Land, are to operate in accordance with best mining practices, and to restore mined areas to a condition which satisfies Traditional Owners and the Northern Territory government. In this way, Nabalco has implemented a policy of continuous rehabilitation of land affected by mining since the early 1970s. The emphasis has been on the re-establishment of a self-sustaining indigenous Eucalyptus forest ecosystem with key species which identify with the 'Yolngu' people's genealogy. Currently at Gove, some 125 ha are mined and rehabilitated each year with 2000 ha having been returned to indigenous eucalyptus forest communities to date. Plants from soil-born seed emerge from placed top soil within months after rain. Grass, forbs and acacias are the dominant species developing on reshaped mined land, whereas upper canopy species are poorly represented and need to be re-introduced by direct seeding (by either hand or mechanical broadcast). Pasture species, *Chloris gayana* Pioneer and *Sorghum almum*, are broadcast with superphosphate (200 kg/ha). The objective of early establishment of short-lived species is to minimise erosion, reduce high soil surface temperature and to provide micro-habitats for early recolonisation of meso-fauna.

Selecting pioneer plants with specific qualities is vital to the land-rehabilitation process. Depending on the circumstance, these qualities include the capacity to grow in nutrient-poor conditions, nitrogen-fixing abilities, fire tolerance, and the aptitude to act as foci for the establishment of fauna and other flora.

Two key species known to have the ability to act as foci were selected as pioneers to rehabilitate twenty year old mined pits in Sierra Leone. They were *Acacia leptocarpa* (endemic to north east Arnhem Land) and a broad-leafed tufted grass, *Paspalum plicatulum*. Both species can host rhizobia which are crucial to improving soil nutient balance during soil restoration. In Australia and West Africa, the 5 m high *Acacia* tree produced functioning root nodules in which bacteria fixed nitrogen. Analysis of *Acacia* phyllodes in Sierra Leone showed N contents of up to 2.58% which augmented soil N after leaf-fall. *Ramaria* sp, an ectomycorrhizal fungus, is found with *Acacia leptocarpa* on five year old rehabilitated sites, both in Gove and Sierra Leone. Reddell et al (1992) indicated that mycorrhizal fungi infection increases with time. The acacia tree is also chosen by birds to perch and nest, which leads to seed dispersal and hence to early plant recolonisation within the sites.

3 The role and activity of termites

In tropical regions, certain species of termites have been regarded as the tropical analogue to the earth worm by performing functions similar to earthworms, restoring soil profiles and utilising organic matter (Lee & Wood 1978). Social insects, such as the termite, are among the most successful of organisms when it comes to utilising the resources and habitat of their environment (Cragg 1978). Termites also bring soil from lower strata to the surface and hence increase nutrient availability to plants (Majer 1989). These become micro-habitats that are beneficial to many other organisms.

The effects of termite recolonisation were studied under varying times since mine site rehabilitation and compared with analogue sites. The number and species of termites upon recolonisation depends on the availability of food. The degree of recolonisation and behaviour of the termites on rehabilitated mined land and residue ponds was studied by random observation and cellulose baiting. Burrowing within reinstated soil horizons and in soil clods under stones, litter and timber and in live plant tissue was observed.

Cellulose baiting to attract termites uses toilet rolls, cardboard bricks and leaf litter (Wood & Sands 1978, Reddell et al 1992, Spain pers comm, Hinz 1997). By baiting, information on the activity and number of species present is provided. Using line transects, the baits are laid out at 10 x 5 m intervals within the five to twelve year old rehabilitated areas. With the litter removed, one end of the bait is placed firmly on the ground ensuring contact with the soil. The baits are then covered up with branches or dry grass and leaves to avoid disturbance by vertebrates. After a fixed period of 21 d exposure, the intensity of the attack is calculated. Readings are made on the scale of 0–5 with the complete destruction of the bait scoring 5. Figure 1 compares termite activity counts from reclaimed land and pre-mined vegetation from Gove and Sierra Leone in 1993.

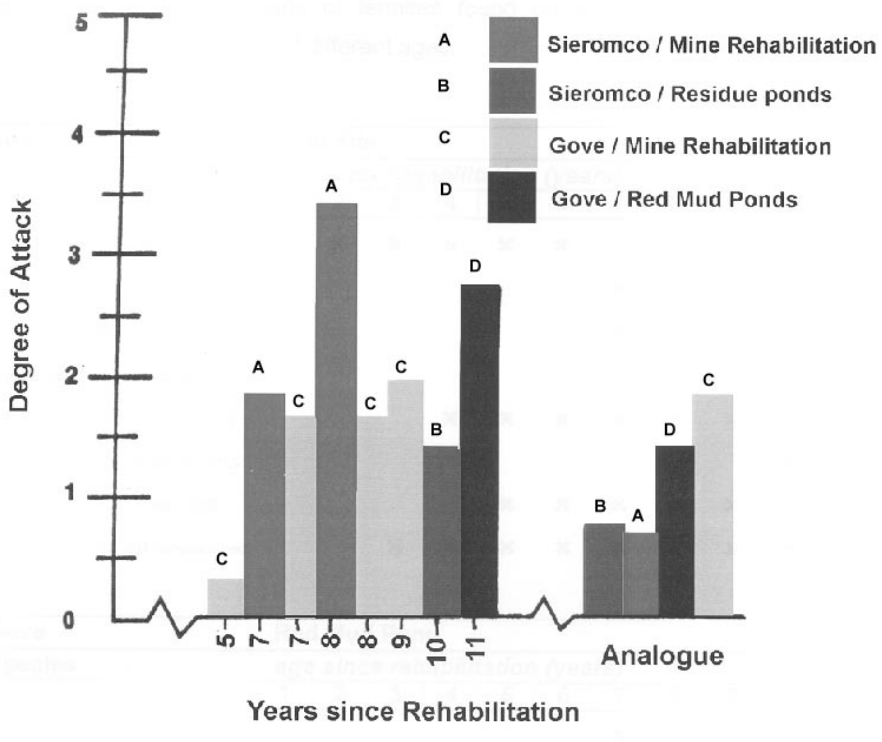

Figure 1 The level of termite activity and the degree of attack on cellulose baits, on rehabilitated mined land and analogue sites of various ages over time at the Gove and Sierra Leone bauxite mines were studied and analysed. The data was collected during Dry and Wet season conditions.

According to the data, the activity of termites on reclaimed areas increases with the time since rehabilitation, a trend which should continue as part of nutrient cycling and an increase in food supply. Before mined areas were rehabilitated, soil analysis of the A-horizon showed that the level of organic matter was as low as <1%. Within seven years of reclamation the levels had risen to 2.2%. Significantly, in the vicinity of plants where termites and micro-fauna had been active, levels had risen further. Under tufted grass, *Heteropogon contortus* and *Paspalum plicatulum*, levels had risen to 4.4% and under the litter of *Acacia leptocarpa* to 11%.

A considerable mass of soil can be brought to the surface by continual mound-building and litter feeding termites. For example, studies at Gove on the rate of subsoil excavated and used in mound building by the grass harvester of the genus *Amitermes vitiosus* on a four year old rehabilitated bauxite area at Gove (using line transects) amounted to 24 Mg ha^{-1}. Modification of soil profiles was also recorded with the ant *Brachyponera lutea*, a subterranean species which brought up 2.5 Mg ha^{-1} of B-horizon material and *Apterogryllus pedestris* (Walker), King Cricket (an early coloniser), which excavated 0.104 Mg Ha^{-1} of mineral soil to the surface. Furthermore, the ant *B. lutea* was recorded colonising the twelve-year old rehabilitated red mud tailings pond.

The termites *Microcerotermes serratus* (Froggatt) and *Tumulitermes* sp also carry out physical and organic modifications to the soil by raising material from B-horizons and placing it on and between leaf litter. Sandwiched between the soil, mycelium growth breaks down the litter and makes it palatable to the termites. The combined role of termites and fungi are instrumental to litter turnover.

Tumulitermes sp, an undescribed subterranean species (Dr LR Millar pers comm), colonises rehabilitated mined land within 3 years of soil emplacement and direct seeding. Equally significant, *Tumulitermes* sp colonised red mud tailings within 10 years of capping and direct seeding and planting of tree species. *Tumulitermes* sp (a non-mound builder) is most active within the top 30 cm of soil. Its subsurface galleries are often found under stones, old timber and earth clods and at times, fragments of shredded grass are found in underground chambers.

The following field observations were conducted (with microscpic identification) of food storage in subterranean nests of *Tumulitermes* sp. Observations of their fungus nurturing were carried out during the early Wet season months of October to January, 1994–98, at Gove.

The following were observed:

- walls of galleries are lined with dark liquid excrement;
- lodged to wall excrement are finely shredded fragments of fresh root and basal leaf sheaths, excised from grass;
- preferred fresh frass, identified as the indigenous grass, *Heteropogon contortus*, shredded from roots and basal leaf sheaths found throughout galleries and runways;
- charred plant fragments lodged to excrement along chamber walls (post fire observation);
- small dried pellets of finely shredded grass fragments stored in chambers — mentioned by Lee and Wood (1978) with species *Tumulitermes tumuli* (Froggatt);
- leaf cutlets (possibly Eucalyptus) embedded in soil faeces;
- dark faeces pellets and soil faeces pellets partly or fully covered with mycelium growth and droplets of honeydew. Signs of possible fungus-growing activity. The honeydew droplets identified as from *Antonina graminis*, a host on *Heteropogon contortus*;
- tunnelling and galleries within soil clods noted (some contained frass) on 3-year-old rehabilitated site.

No attacks were recorded when baiting with toilet rolls which indicated that *Tumulitermes* sp is a grass/humus-feeding, fungus-growing termite. Fungus growing activities of *Tumulitermes* sp were also observed with frequently burned *Eucalyptus tetrodonta* analogue sites. It was observed that the workers deposit B-horizon soil between dry leaf sheets which are then sealed off with a selection of leaf fragments, charred litter and soil, and glued together with a salivary secretion. Mycelium growth developed within days on leaf sheets buried under this blanket.

The mound-building termite, *Microcerotermes serratus*, is widely distributed across rehabilitated mined land ranging from 4 to 29 years old, and 10 year old vegetated red mud tailings ponds and the native forest environment. Its small carton mounds, 15–21 cm high, are vulnerable to fires. *Microcerotermes* species were collected from cellulose baits, and from dead wood and leaf litter (L- and F-horizons). They were found in earth runways on living *Eucalyptus* and *Acacia* spp in Gove and in Sierra Leone. In Gove they were observed feeding on roots and leaves of grass *Heteropogon triticeus*, often killing the entire plant. This and other species were studied in environments rehabilitated to indigenous Eucalyptus forests (table 1).

Table 1 The major groups of termites found on sites rehabilitated to native forest/woodland vegetation of different ages

Gove	**Mine site**											
Species	**Age since rehabilitation (years)**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Amitermes vitiosus		X	X	X	X	X						
Heterotermes vagus							X	X	X	X		
Heterotermes venustis							X	X	X	X		
Mastotermes darwiniensis										X	X	X
Microcerotermes serratus				X	X	X	X	X	X	X	X	X
Nasutitermes longipennes										X	X	X
Schedorhinotermes spp					X	X	X	X	X	X	X	X
Tumulitermes sp (undescribed)			X	X	X	X	X	X	X	X	X	X

Gove	**Red Mud Pond**											
Species	**Age since rehabilitation (years)**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Amitermes meridionalis							X	X	X	X	X	X
Microcerotermes serratus							X	X	X	X	X	X
Mastotermes darwiniensis								X	X	X	X	X
Nasutitermes longipennes									X	X	X	X
Schedorhinotermes spp								X	X	X	X	X
Tumulitermes sp (undescribed)								X	X	X	X	X

Sierra Leone	**Mine areas and residue ponds**									
Species	**Age since rehabilitation (years)**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Ancistrotermes cavithorax										X
Cubitermes nr. *Proximatus*					X	X	X	X	X	X
Macrotermes bellicosus							X	X	X	X
Microcerotermes fuscotibialis						X	X	X	X	X
Pericapritermes heteronotus										X

Conclusion

Termites are useful ecological indicators for successful soil and vegetation development on disturbed land in humid tropical environments.

In land rehabilitation, termites help to create healthy, self-regulated vegetation systems that integrate with the surrounding landscapes and build structures and functions equal to those of the pre-disturbed system. They are reliable in signalling the health and stress factors of a system with predictable response.

Termite numbers and activity levels increase over time as shown from studies of 3–10 year old rehabilitation sites at Gove and in West Africa, and thereafter become stable. However, if stress is applied to the environment (eg frequent fires), the number of termites and the soil turnover activities of key species decline. At that point, wood-feeder numbers increase, (eg *Mastotermes darwiniensis* (Froggatt)), leading to the attack of a large range of plant species and the risk of turning a diverse plant community into a mono plant community or open grassland. Under these conditions, *M darwiniensis* will attack roots of living plants and ringbark healthy and stressed trees.

At Nabalco's bauxite mine, Gove, the value of termites as ecological indicators in land and tailings rehabilitation have been recognised for over 25 years.

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State of the Environment Reporting: Links with minesite rehabilitation

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Abstract

The main purpose of State of the Environment (SoE) reporting is to provide clear, objective and scientifically credible information about the condition of Australia's environment to the Australian community. The three main functions of SoE reporting are 1) informing (providing information), 2) tracking (assessing change), and 3) alerting (signalling events, effectiveness and gaps).

State of the Environment reporting responds to calls made in Australia's *National Strategy for Ecologically Sustainable Development.* Internationally it fulfils obligations for *Agenda 21* (UNCED Rio '92). Its application in relation to minesite rehabilitation is discussed here.

History of SoE reporting

An SoE *Discussion Paper* was released for public comment in 1992 in response to *National Strategy for ESD*. The State of the Environment Advisory Council, chaired by Professor Ian Lowe, was established by the Minister in early 1994, to guide the development and implementation of the reporting program. In late 1994, a strategic *Framework Document* (DEST 1994) was developed by Council in response to feedback on the 1992 *Discussion Paper*. It outlined a report structure, an adaptation of a Pressure-State-Response Model, the major themes to be covered and a reporting cycle.

Current situation

Since the release of '*Australia: State of the Environment 1996'*, the Australian State of the Environment Section has been developing environment indicators. These indicators are designed to serve as a foundation for future State of the Environment reporting products.

The goals of the environmental indicator development program were to:

- identify a key set of environment indicators for national State of the Environment reporting;
- identify a core set of environment indicators for common reporting across jurisdictions;
- secure data sources to support the indicators;
- develop models and stores of baseline information to help interpret the indicators;
- ensure that the indicators have broad acceptance; and
- promote research to enable better interpretation and use of indicators.

These indicators are set in a modification of the Pressure-State-Response model called Condition-Pressure-Response (C-P-R). Indicator reports are now available for each of the seven themes: Inland Waters, Estuaries and the Sea, the Land, Biodiversity, the Atmosphere, Human Settlements, and Natural and Cultural Heritage. State of the Environment reporting for the Australian jurisdiction is now a requirement under the *Environment Protection and Biodiversity Conservation Act 1999*. Reports are required every five years and the next one must be produced by 31 December 2001.

Progress towards next report in 2001

The Australian State of the Environment Section has been working to identify data sources for indicators in preparation for the next report. The Australian State of the Environment Committee has been appointed to oversee production of the next report. The Committee is chaired by Professor Bruce Thom and its members are Associate Professor Bob Beeton, Professor Peter Cullen, Dr Libby Mattiske, Ms Wendy McCarthy, Mr Bill McLennan, Dr Russell Reichelt, Dr Alan Reid and Dr Gaye Sculthorpe.

Links with mine site rehabilitation

The sets of indicators developed for national State of the Environment reporting contain three indicators that specifically mention mining and mine site rehabilitation.

Land 1.1C Total area of minesite bare ground, by catchment

Description: Areal extent of open mine sites, quarries and associated earthworks by catchments, providing a measure of the potential for water erosion from exposed minesites. This indicator is listed under the issue of accelerated erosion and indicates the potential of minesites to contribute to erosion.

Land 6.5 Quality of mining operations relative to total mine sites, and regulation requirements, by drainage basin

Description: The number of mine sites with ongoing and final rehabilitation programs that are effective and operational, relative to the number of registered and located sites, per reporting period. This indicator is listed under the issue of soil and land pollution and indicates the potential for contamination from mine sites.

Inland Waters 3.7 Minesite remediation

Description: The number of mines discharging drainage that are remediated per year. This indicator is listed under the issue of water quality and relates to the potential for drainage from mine sites to impact upon water quality.

As mining occupies a very small area it does not have many specific indicators. However, many of the indicators are relevant to issues associated with mine site rehabilitation. The themes use a range of issues to provide a framework for SoE reporting. Three themes, land, biodiversity and inland waters, are particularly relevant to the issue of assessing rehabilitation. For example, indicators for the Land (Hamblin 1998), Biodiversity (Saunders et al 1998) and Inland Waters (Fairweather & Napier 1998) themes are listed under a range of major issues:

Land

- Accelerated erosion and loss of surface soil
- Physical changes to natural habitats
- Hydrological imbalance

- Introduction of novel biota into native habitats and communities
- Nutrient and salt cycling
- Soil and land pollution

Biodiversity

- Human population growth, density and demand on natural resources
- Clearing, fragmentation, degradation of native vegetation or marine habitat
- Alien or exotic species
- Genetically modified organisms
- Pollution
- Altered fire regimes
- Human Induced climate change
- Harvesting
- Genetic diversity
- Species diversity
- Ecosystem diversity
- Increase in knowledge of biological diversity
- Involving the community in conservation
- Australia's International obligations

Inland Waters

- Groundwater
- Human health
- Environmental water quality
- Surface water quality
- Physical change
- Biotic habitat quality
- Effective management

Some of these issues are clearly irrelevant to assessing the rehabilitation of a mine site. However, the others may provide some guidance to what issues and factors might be considered in regard to assessing the progress towards rehabilitation of a mine site.

Methods of assessment

A review of mine site rehabilitation in the wet-dry tropics of northern Australia (Corbett 1999) lists five approaches to assessing the success of rehabilitation:

1 Quantitative ecological assessment

2 Ecosystem functional analysis

3 Remote sensing

4 Faunal recolonisation

5 Other indicators of ecosystem recovery.

The indicators used for State of the Environment reporting incorporate elements of all the above approaches. Some species abundance indicators in the biodiversity theme relate to quantitative ecological assessment. Some indicators within the land theme relating to hydrological imbalance are based on ecosystem functioning and others rely on remote sensed data. Faunal recolonisation and some of the other indicators of ecosystem recovery are less relevant to state of the environment reporting although some indicators are based on them.

Relevance of SoE indicators to minesite rehabilitation

Can indicators developed for SoE reporting contribute to the debate on assessing rehabilitation of this or any other minesite? Two factors are important here: time and scale. Indicators that have been developed for national reporting may not always be relevant at finer scales although where they are based on fundamental measures of ecosystem function scale there may be less of a problem. Time may be more of a problem in that these indicators are designed to be measured at regular intervals to provide a temporal perspective. A measure at one point in time is not necessarily designed to be an indicator of future performance, although measurement through time will provide trends. In comparison, in deciding whether the rehabilitation of a mine site is successful, the measurements or indicators used must be able to provide some assurance of future performance.

Developing and choosing indicators

Some of the criteria used for selecting national environmental indicators may assist the debate over selecting indicators for the success of rehabilitation. A selection of these criteria is listed below.

Each indicator should:

- serve as a robust indicator of environmental change;
- reflect a fundamental or highly valued aspect of the environment;
- provide an early warning of potential problems;
- be capable of being monitored to provide statistically verifiable and reproducible data that show trends over time and, preferably, apply to a broad range of environmental regions;
- be scientifically credible;
- be easy to understand;
- be monitored regularly with relative ease;
- be cost-effective;
- have relevance to policy and management needs;
- where possible and appropriate, facilitate community involvement; and
- where possible and appropriate, use existing commercial and managerial indicators.

Some potentially useful indicators

As noted previously, SoE reporting is based on seven themes with three having particular relevance to assessing progress on rehabilitation. Tables 1–3 (following) list some of the indicators from these themes that may be particularly relevant to this issue. Whilst these indicators are designed to operate at a national scale these particular ones may be useful at a smaller scale. They also provide an indication of the characteristics of the rehabilitated sites that should be monitored. The relevance, usefulness or otherwise of these issues and particular indicators will only be established by further discussion at the workshop.

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Table 1 Some potentially relevant indicators from the Land theme (Hamblin 1998)

Issue	Details	C, P, R†
1	**Accelerated erosion and loss of surface soil**	
L 1.1	Change in total exposed soil surface contributing to erosion, as a percentage of land area per landcover region, stratified by major land use	P
L 1.1C	Total area of open minesite bare ground, by catchment	P
L 1.1D	Area of unsealed roads and earthworks as a proportion of total land area, by catchment	P
L 1.2B	Non-domestic vertebrate herbivores	P
L 1.3	Change in area that is impervious as a proportion or total area, by urban and rural catchments	P
L 1.4	Surface soil loss index	C
L 1.5	Gullying index per major catchment	C
L 1.6	Change in dust storm index relative to number of high wind events by AERs and landcover regions	C
2	**Physical changes to natural habitats**	
L 2.4	Landcover change: proportion of each region covered by forest, wood, shrubs and grasses compared with 1990 baseline, by landcover	C
3	**Hydrological imbalance**	
L 3.1	Ratio of area of catchment under perennial: annual vegetation, as proportion of total catchment (report also by State)	P
L 3.3	Percent area of land affected by dryland salinity and by acidity, by catchment and AER	C
L 3.4	Variation in plant water utilisation with landcover change	C
4	**Introduction of novel biota into native habitats and communities**	
L 4.1	Rate of extension of exotic species into each IBRA, and of change in their abundance	P
L 4.1 A	Number of reports of all, and of new, weeds, pests and diseases per AER and IBRA region	P
L 4.4	Weed infestation index: rate of spread x habitats affected	C
5	**Nutrient and salt cycling**	
L 5.1	Total nutrient export of Nitrogen, Phosphorus and Potassium from each AER and drainage basin	P
L 5.1A	Rates and distribution of Nitrogen, Phosphorus and Potassium accessions into each AER and drainage basin	P
L 5.1 B	Sources of P derived from land activities reaching rivers by catchment	P
L 5.2	Terrestrial carbon (organic matter) loss rate by IBRA region	P
L 5.3	Change in area and location of salinised land, compared across regional catchments and AERs	P
L 5.4	Net nutrient balance for major elements Nitrogen, Phosphorus and Potassium per year by land use mapped across IBRA regions and drainage basins	C
L 5.5	Rates of land carbon (organic matter) sequestration by AER and IBRA region	C
L 5.6	Change to net primary productivity by IBRA regions, grouped by catchments	C
6	**Soil and land pollution**	
L 6.1	Total immobile contaminant load on land area by catchment	P
L 6.3	Change in status of highly contaminated sites per catchment	C
L 6.4	Condition of environments surrounding high-radiation sites	C
L 6.5	Quality of mining operations relative to total mine sites, and regulation requirements, by drainage basin	C

† C – Condition; P – Pressure; R – Response

Table 2 Some potentially relevant indicators from the Biodiversity theme (Saunders et al 1998)

	Clearing, fragmentation, degradation of native vegetation or marine habitat	**C, P, R†**
2.1	Extent and rate of clearing, or major modification of natural vegetation or marine habitat	P
	Alien or exotic species	
3.1	Rate of extension and abundance of exotic species into each IBRA	P
3.2	Pest numbers	P
	Altered fire regimes	
6.	Areal extent of altered fire regimes	P
21.	Reducing the impacts of altered fire regimes	R
	Genetic diversity	
9.1	Number of sub-specific taxa	C
9.2	Population size, numbers and physical isolation	C
	Species diversity	
10.1	Number of species	C
10.2	Estimated number of species	C
	Ecosystem diversity	
11.1	Ecosystem diversity	C

† C – Condition; P – Pressure; R – Response

Table 3 Some potentially relevant indicators from the Inland Waters theme (Fairweather & Napier 1998)

	Groundwater	**C, P, R†**
1.1	Depth to watertable	C
1.2	Groundwater salinity	C
	Environmental Water Quality	
3.1	Guideline trigger levels reached	C
3.2	Algal blooms	C
3.3	Nutrient loads	C
3.4	Chemical residues	C
3.5	Pesticide exposure	P
3.6	Pollution point sources	P
3.7	Minesite remediation	R
3.13	Instream salinity trends	C
	Physical change	
5.1	Vegetated streamlength	P
5.2	Extractive industries	P
5.3	Catchment clearance	P
	Biotic Habitat Quality	
6.1	AUSRIVAS survey ratings	C
6.2	Frogwatch records	C
6.3	Fish kill records	C
6.4	Waterbirds	C
6.5	Habitat loss	P
6.6	Exotic pest flora and fauna	P
6.7	Wetland extent	C
6.8	Pest control	R

† C – Condition; P – Pressure; R – Response