5

Wetland management issues and threats

CAN ECOLOGICALLY SUSTAINABLE DEVELOPMENT (ESD) HELP THE MAGELA WETLANDS?

P Mc BRIDE

Office of the Supervising Scientist,
PO Box E348, Queen Victoria Terrace,
Parkes, ACT 2600

ABSTRACT

In the last 30 years, environmental deterioration has become a major public concern. Government participation in environmental issues is a more recent development, but is now significant at both national and international levels. In Australia the principal outcomes have been the Intergovernmental Agreement on the Environment (May 1992) and the National Strategy for Ecologically Sustainable Development (December 1992). These provide goals and objectives from which local environmental protection strategies can be developed. By using the ESD Objectives of maintaining biodiversity and ecological processes, and following the Precautionary Principle, effective strategies to monitor and protect the environment of wetlands in the Alligator Rivers Region can be developed. These can aid the selection of site specific ecological indicators that are relevant and defensible. Because of their widespread use by scientists, government and the general public, there is an urgent need to establish generally accepted and clear meanings for environmental terms like biodiversity and ecological integrity.

Keywords: ESD, sustainable development, IGAE, biodiversity, biological diversity, environmental protection

1 Background

The background to Ecologically Sustainable Development (ESD) stretches back to the beginnings of public awareness of the environment as a matter of concern for everyday life. Up to about the seventies, the general public did not perceive environmental deterioration as something that could significantly affect its health and quality of life. The bush and the wider world environment beyond were seen as limitless and capable of absorbing whatever insults that development threw at them. Sights like the hills of Queenstown denuded by the activities of the Mt Lyell copper mine were perceived as quaint demonstrations of taming the wilderness. For example a detailed history of the Mt Lyell mine in Tasmania published in 1967 did not report on the impacts on the King River produced by released mine tailings. The downstream reach of this river is sterile, or as a recent survey reported 'has water quality highly inhibitory to animal and plant life' (Anon 1994).

It was not until the publication of *Silent Spring* (Carson 1962) that environmental deterioration received major publicity. Unlike previous books forecasting environmental catastrophe, this one became a best seller world wide. The costs of environmental degradation to wildlife and human health were brought home to the general population in this vivid if rather sensational account of the disastrous impacts of the unrestricted use of pesticides and other environmental chemicals.

In Australia the first nationwide environmental issue arose in 1967, when the Tasmanian Government made public its decision to flood Lake Pedder. Previously Lake Pedder had been of interest to only small sections of the community, such as the Hobart Walking Club which in 1955 was successful in having the area around the lake declared a National Park (Doyle 1995). Over the next three years Lake Pedder became a national environmental issue and the environment became part of the political landscape. The first 'green' political party, the United Tasmania Group, campaigned specifically on this issue and in 1972 came within 200 votes of winning a parliamentary seat (Doyle 1995).

The next major environmental confrontation occurred in 1979 over the proposal to dam the Franklin River. Unlike the Lake Pedder flooding, the outcome this time was in favour of the environmentalists. As an indication of the development of environmental politics, the matter was resolved at a national level rather than a state level and was supported by an international agreement to preserve World Heritage areas. The strength of environmental issues in the political arena was further demonstrated in the 1990 Federal Election where it was acknowledged that the environmental vote played a critical role in the Labor victory.

The public interest in the environment as a national issue of long term importance led to the development of government policies for environment protection. The major initiative was the Ecologically Sustainable Development (ESD) Strategy. This was a derivative of the 'sustainable development' concept developed in the Brundtland Commission Report (World Commission on Environment and Development 1990). The objective of the ESD process is to provide a policy strategy for the Australian community for the longer term - defined for practical purposes as up to 40 years. The development of ESD was of epic proportions and included representatives from government, industry, CSIRO, and union, environmental and consumer organisations. The exercise involved 12 working groups, about 250 people, over 200 submissions of community views and cost about $20 million.

Development began in June 1990 with the release of a Commonwealth Discussion Paper *Ecologically Sustainable Development.* In August 1990 the Prime Minister announced the formation of nine ESD Sectoral Working Groups to advise on future ESD policy directions. Following the release of Working Groups reports, Working Groups Chairs intersectoral reports and Working Group reports on intersectoral issues and greenhouse, in May 1992 the Heads of Government agreed to release a draft strategy for public comment. Finally, in December 1992 the Council of Australian Governments endorsed the National Strategy for ESD (Anon 1992a), and agreed that the future development of all relevant policies and programs, particularly those that are national in character, should take place within the framework of the ESD Strategy and the Intergovernmental Agreement on the Environment.

The goal of ESD is

- to achieve development that improves the total quality of life, both now and in the future, in a way that maintains the ecological processes on which life depends.

The Core Objectives of ESD include

- the protection of biological diversity and the maintenance of essential ecological processes and life-support systems.

The Guiding Principles of ESD include the Precautionary Principle which states

- 'where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation'.

There is no universally accepted definition for ESD. In 1990 the Australian Government suggested the definition: 'using, conserving and enhancing the community's resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased'. Only part of the ESD strategy is directed towards 'natural' environmental matters. Much has been defined at sectoral levels which do not relate directly to natural areas and wetlands (eg health aspects, population, urban issues, the coastal zone, Aboriginal issues).

A development closely related to ESD was the Intergovernmental Agreement on the Environment (IGAE) (Anon 1992b). This embodies principles of environmental policy including the following:

- where there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation
- conservation of biological diversity and ecological integrity should be a fundamental consideration.

The IGAE philosophy of environmental protection is essentially similar to the ESD strategy. The Precautionary Principle is the same, and the IGAE conserves ecological integrity while ESD maintains ecological processes. Both provide a mechanism for the integration of environmental and economic considerations in decision making and can be used as a basis for developing local environmental protection strategies.

The rapid development of the environment as a community and government issue has outstripped the development of its terminology. Concepts and philosophies of environmental protection and environmental management are still in their infancies and a number of terms (buzzwords) have been coined or adapted to serve the needs of scientists and managers. These include ecosystem health, biological diversity, biodiversity, ecological integrity, biological integrity, and environmental integrity. Most of these terms are now in the public domain and there is an urgent need to crystallise meanings to avoid confusion when the same words are used by scientists, managers and the public. At present some terms are defined differently by authoritative sources and two definitions of biodiversity/biological diversity are set out below to illustrate the problem:

- 'Biological Diversity' means the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (*Biological Diversity Convention, Rio Summit, June 1992*).
- Biodiversity comprises the variety of life on earth. It is generally seen as encompassing three main levels of organisation: *genetic diversity* - the total range of genetic information contained in the genes of all living things; *species diversity* - the variety of species of organisms on earth; and *ecosystem diversity* - the variety of habitats, biotic communities, and ecological processes and interactions that characterise the biosphere (*Ecologically Sustainable Development Working Group Chairs, 1992*).

The two meanings are not the same because the second contains an important additional concept, that of ecological processes and interactions. In fact it would take only a further strengthening of this aspect to enable biodiversity to encompass the concept of ecological integrity, which has been defined as:

- 'The ability to support and maintain a balanced, integrative, adaptive community of organisms having a species composition, diversity and functional organisation comparable to that of the natural habitat of the region' (ANZECC Guidelines, page 2–10).

The ESD strategy (and the IGAE) provide objectives for environmental protection which can form the basis of local strategies. The indicators or measures used to determine whether the objectives of ESD are being met can include both biological and physico-chemical data. Three general types of indicator are necessary for a comprehensive approach: compliance indicators, diagnostic indicators, and early warning indicators (Cairns et al 1993).

- Compliance indicators are used to judge whether general goals and specific ecosystem objectives are being met.
- Diagnostic indicators can suggest corrective actions in the event that objectives are not being met.
- Early warning indicators enable impending problems to be identified before they exert substantial impact on the ecosystem. This enables a predictive instead of a reactive style of management to be used.

In many cases, the indicators most useful in judging compliance will not be helpful in determining why objectives are not being met or in providing early warning of impending problems. For any particular locality and monitoring objectives there will be a minimum number of ecosystem measures which need to be carried out to fulfil the objectives. Trade-offs between desirable characteristics, costs and quality of information are inevitable when choosing indicators for management use.

Irrespective of the number of indicators, no monitoring program can be infallible. Cairns et al (1993) point out that although the problems arising from methyl mercury could have been predicted if simple sediment-water microcosms had been included in the test protocol, eggshell thinning in birds resulting from DDT uptake could not have been predicted by any available test models and procedures.

There is a need to soon develop generally agreed guidelines for the indicators that are used to assess ecosystem condition. A number of approaches have been developed to provide ecosystem condition measures which can be used to assess biodiversity and ecological integrity. As with the terminology, there are as yet no universally accepted approaches, ie there is no 'kit' to provide guidance for devising a program to monitor ecosystem condition in a new locality.

2 Applicability of ESD to Magela wetlands

Protection of the Magela wetlands has focussed on avoiding impacts from the Ranger Uranium Mine. This mine presently operates under Environmental Requirements (ERs) which are prescriptive and process based rather than outcome based.

Limitations are placed on practices and procedures (eg ER7(f): .... the Joint Venturers shall not release or allow to flow from a Restricted Release Zone liquid water other than the natural sub-surface flow of groundwater ...) rather than on outcomes.

The mine is required to operate in accordance with Best Practicable Technology (ER44) which is defined in the Environmental Requirements as 'that technology .. which produces the minimum environmental pollution and degradation that can reasonably be achieved having regard to a number of factors including best practice elsewhere in the world, economics, evidence of detriment or lack of it, the location of the project, the age and effectiveness of equipment, and social factors'. This implies that some level of detriment would be acceptable but none of the stakeholders has been prepared to specify a level of acceptable detriment.

The approach adopted by the Supervising Scientist has been to seek control measures and monitoring procedures that will ensure and demonstrate that the environment has not been harmed and probably will not be harmed by Ranger operations. In the absence of a suitable definition of acceptable change, the Supervising Scientist concluded that the only practical target is that mining operations produce no observable biological effect in a suitably defined monitoring program comprising a number of organisms selected from different trophic levels and Phyla and using a range of sensitive endpoints.

The ESD Strategy offers an alternative approach which also does not require a definition of acceptable change. The ESD objectives are outcome based, defensible, and can provide the basis of site specific environment protection strategies for the Magela wetlands. Under the present 'no observable biological effect' strategy, changes which are measurable but do not threaten the health of the Magela wetlands could still be treated as a failure of environmental protection. Although the same indicators may be used in both of the strategies, their interpretation is more clearly outcome based if the ESD Strategy objectives of maintaining biodiversity and ecological processes are used.

3 References

Anon 1992a. *National Strategy for Ecologically Sustainable Development.* AGPS Canberra

Anon 1992b. *Intergovernmental Agreement on the Environment.* AGPS Canberra

Anon 1994. Environmental Review 1993, Mt Lyell Mining Leases 30M/80 and 28M/83 Gutteridge Haskins & Davey Pty Ltd, unpublished report

Cairns J Jr, McCormick PV & Niederlehner BR 1993. A proposed framework for developing indicators of ecosystem health. *Hydrobiologia* 263, 1–44

Carson R 1962. *Silent Spring.* Houghton Mifflin, Cambridge, Mass: Riverside Press

Doyle J 1995. *Turning green. Wild Summer 1995* (55), 60–3. Wild Publications Pty Ltd, Prahran, Victoria.

Ecologically Sustainable Development Working Group Chairs. 1992. *Intersectoral Issues Report.* AGPS, Canberra

World Commission on Environment and Development 1990. *Our Common Future,* Australian Edition. Oxford University Press, Melbourne.

INDIGENOUS PEOPLE AND SCIENCE

J CHRISTOPHERSON

Aboriginal Traditional Owner

ABSTRACT

Aboriginal people have developed a vast and comprehensive knowledge of the environment of northern Australia, such as in Kakadu National Park. This covers care and use of the land based on experience that has been passed on by one generation to the next. The knowledge of food values and other uses of plant and animal material may not be based on understanding causal relationships, but that does not negate its usefulness to Aboriginal and non-Aboriginal people alike. However, do non-Aboriginal scientists and the public take Aboriginal knowledge seriously? To date, the answer is a resounding NO. But this is changing and if Aboriginal knowledge and wisdom is listened to and combined with modern scientific methods we may actually achieve joint management of places such as Kakadu with its spiritual and cultural heritage.

1 Introduction

Indigenous peoples have used and occupied Australia for over 40 000 years and that includes the area where we are today, Kakadu National Park.

The survival of Aborigines in this country is based on inheritance. The inherent rights of Aboriginal peoples does not mean solely the right to use and occupy, but includes responsibilities to manage and maintain the land in a way that all people entitled to use it are able to.

To use and occupy requires a certain amount of knowledge, to not only survive, but to be able to thrive within your peoples' defined lands. Responsibilities require that the estate is managed and maintained in a way that ensures that those peoples can thrive.

Knowledge of responsibilities and rights are passed on from person to person, generation to generation over a long period of time. Indeed, it is longer periods of time than required to complete primary, secondary and tertiary education and qualifications.

That knowledge encompasses spiritual, social and the physical environment, such as what plants and animals are edible and those which are not, and those which can be eaten after being treated in a certain manner.

The knowledge passed on also includes what the obligations are to ensure the continued propagation of that food source and who is responsible for that food source. Central to the learning about a particular food source is the history of that food source, how it came into being.

But to be able to thrive Aboriginal peoples needed to have an intimate knowledge of their total environment.

A knowledge of their whole landscape and all things on it, not only where and when to find food sources but all other usable resources. For example medicines, materials for hunting items such as spears, boomerangs and cutting implements; materials for ceremonial activities - ochres and clays; and a knowledge of places where people were not allowed to go, the reasons why and the penalties for not observing one's responsibilities.

Macquarie Dictionary defines '**science**' as:-

1a. a systematic study of man and the physical world based on reproducable observations, measurements and experiments.

1b. the knowledge so gained.

2 a particular branch of knowledge.

3 skill; proficiency

A '**scientist**' is described as:-

Someone skilled in or working in the field of science, especially physical or natural science.

Given the above definitions the non-Aboriginal people have science and scientists that cover all aspects of societies and the environment, but only in those scientist's particular field of expertise and/or interest and in some cases overlapping fields.

As you would all be well aware there are numerous branches of science studying and working in Kakadu:- Botanists; Biologists; Geologists; Hydrologists; Zoologists; Anthropologists and Linguists; Land Managers. The list goes on, dare I mention it, given what has occurred over the past few weeks, you can even get a degree in Political Science. Which is a term I have difficulty coming to grips with - Politics and Science.

2 Where does Aboriginal knowledge fit in with the western concepts of science?

You can get a degree in Aboriginal studies at tertiary institutions, but an Aboriginal is not qualified if he or she stays in their community and learns all that they can of available Aboriginal knowledge.

Knowledge such as the correlation between the Black Wattle flowering and the turtle being fat in the sea. Not a causal relationship but nonetheless a correlation that has been studied for a long time.

Knowing when the Spear Grass seeds that the geese are laying eggs, a non-causal relationship? Or that sugar bag, the bush honey is at its best when a certain tree is flowering, a causal relationship amounts to nothing in western science concepts.

Using the leaves of the iron wood tree wrapped in paper bark and burnt to relieve places of the spirits of deceased persons, may not be considered scientific in the study of that particular tree. But other uses may be in the western sense, that is the bark when boiled produces an antiseptic medicine for cuts and grazes and the timber has qualities unlike any other tree for use as spear tips and other implements.

The Barramundi has been part of the diet of Aboriginal people for many thousands of years, yet x-ray paintings show that the Barramundi was not only a food source but was studied; and indeed knowledge of the habitat and migratory habits of the elusive fish shows more substantial study had occurred.

The use of fire by Aboriginal peoples was, up until now, not understood by non-Aboriginal people except to mention it as fire stick farming.

It was not until disciplines of the sciences studied the causal effects that that perception has changed. Aboriginal people knew for a long time the relationship between fire and the propagation of species and the management and maintenance of the environment.

Aboriginal knowledge which is passed on today took many thousands of years of learning, but unfortunately to be considered knowledgeable today, that is not enough. You need non-Aboriginal knowledge and therein lies a paradox, you can become a scientist studying Aboriginal peoples' culture and language <u>but</u> Aboriginal peoples' knowledge is not recognised as scientific.

There may be a number of reasons for this, firstly, the perceptions that non-Aboriginal people have of the Indigenous peoples of this country.

Secondly, because the information is not documented scientifically and the method of passing on that knowledge is not considered scientific. A botanist may not consider a song or dance about a tree as valid information.

And thirdly, and perhaps most importantly is that if Aboriginal knowledge was recognised as valid information in its entirety in the scientific world then it would cause dilemma when confronted with differing views over best practicable technology in managing and maintaining the environment; and recognition of Intellectual Property Rights.

3 Intellectual Property Rights

Whose view should prevail, the holistic view of Aboriginal peoples or the strict and at times narrow view of western science which has shown, at times, elements of risk or unknown factors.

This is a difficult question to answer, but until such time as people stop treating Indigenous peoples' knowledge and cultural practice as mythology and treat this knowledge including mythology and spiritual beliefs as valid information, then conflict will remain.

I do believe, however, that the winds of change are upon us and that if people in the western sciences show empathy with Aboriginal peoples' rights, responsibilities, knowledge and mythology, then they will truly be able to achieve joint management in maintaining Aboriginal peoples' lands as National Parks for all peoples.

HISTORICAL PHYSICO-CHEMICAL WATER QUALITY DATA FOR SOME WETLANDS OF THE ALLIGATOR RIVERS REGION, NORTHERN TERRITORY

PH WOODS

Northern Territory Department of Mines and Energy,
GPO Box 2901, Darwin, NT 0801

ABSTRACT

The Alligator Rivers Region in the Northern Territory is well known for its wetlands and its mineral deposits. Four major uranium deposits were discovered between 1969 and 1972. When the mines were proposed, an extensive environmental inquiry was initiated by the Commonwealth, which included consideration of wetlands, as there is potential for any mining to adversely affect them. That, and several studies carried out once mining commenced in 1979, were based on short-term observations, although since then some medium-term studies have been conducted. In an area of recognised large seasonal and annual variations, longer term studies have been lacking.

Both the mining companies and the local supervising authority established extensive environmental monitoring programs, which included monitoring of many wetlands near or downstream of the mines. Extensive physico-chemical water quality data up to 20 years old are stored on the Northern Territory Department of Mines and Energy water quality database, much of which has never been interpreted. This data bank has potential to yield an understanding of the variation of water quality in many of the wetlands of the Region.

Forty-five Alligator Rivers Region sites in the data base pertain directly to wetlands, along with a similar number of in-stream sites. Data from Gulungul Billabong, Ja Ja Billabong and the Magela Floodplain outfall are examined here. None of these has been noticeably affected by mining activities. The annual patterns in electrical conductivity, pH, and the major ions Ca, Mg, Na, K, HCO_3, *Cl and* SO_4 *are demonstrated to be relatively consistent, but the dangers of characterising the variations of these parameters based on short-term records are easily demonstrated.*

Keywords: Alligator Rivers Region, wetlands, water chemistry

1 Introduction

The Alligator Rivers Region (ARR) in the Northern Territory is well known for its wetlands and its mineral deposits. Four major uranium deposits (Ranger One, Jabiluka (now North Ranger) I and II, Koongarra and Nabarlek) as well as several promising prospects were discovered between 1969 and 1972, following earlier mining of several small deposits in the South Alligator Valley (Needham & De Ross 1990). Of these, only Ranger and Nabarlek have been mined to date due to Commonwealth Government Policy. When the mines were proposed, an extensive environmental inquiry was initiated by the Commonwealth, culminating in the Ranger Uranium Environmental Inquiry (RUEI, generally referred to as the Fox Inquiry; Fox et al 1977) which began public hearings in 1975 after a fact-finding study was carried out during 1971-73 (summarised by

Christian & Aldrick 1977). These included consideration of wetlands, as there was perceived to be potential for any mining to adversely affect them (Davy & Conway 1974). As well as initial evaluation of the biology of the wetlands, the physico-chemical characteristics were also investigated. On the latter theme, several studies based on short-term observations were carried out once mining commenced in 1979 (eg six weeks of measurements, Hart & McGregor 1980; four months, Hart et al 1987)). Since then some medium-term studies have been conducted (eg up to 4 years, Walker & Tyler 1982, Walker et al 1984). In an area of recognised large seasonal and annual variations, longer term studies have been lacking.

All four proposed mines carried out detailed Environmental Impact Statements (EISs). The two successful mine operators (Ranger and Nabarlek) established extensive environmental monitoring programs, supplemented by applied research programs, particularly at the longer-lived Ranger mine. The Supervising Authorities of the Northern Territory likewise established very extensive monitoring programs, which include monitoring of many wetlands near or downstream of the mines. The total cost of company and government monitoring was in the order of millions of dollars per year in the early 1980s. Much of the early work is better considered to be of a research or investigative nature, and many of the data have never been interpreted (Woods et al 1994). Up to 20 years of physico-chemical water quality data for many wetlands both affected and unaffected by mining are stored on the NTDME water quality data base. This paper illustrates the type of data available and its potential to aid understanding of the variation of physico-chemical water quality in some wetlands of the Alligator Rivers Region. It is recognised that there are other parameters of importance to the limnology of wetlands, but it must be kept in mind that the data here were collected with the possible impact of mining in mind, rather than strictly to understand the internal functioning of wetlands.

The climate of the ARR is tropical with distinct wet and dry seasons, although the Aboriginal inhabitants recognise at least six seasons (ANPWS 1989). The monsoonal Wet Season is hot and humid, and extends from about October to April, while the Dry Season is warm to hot, with moderate humidity and very little rain. The average daily maximum temperature is close to or above 30°C all year. The onset and cessation of the seasons vary by up to two months from year to year, with the core of the Wet Season extending from December to March, and that of the Dry from June to August. Rainfall may occur during the transitional periods, but October and April may receive no rain at all some years. The strongly seasonal rainfall has a corresponding effect on wetlands, with the period of inundation of wetlands varying from two months up to the full year.

2 Methods

The early history of environmental monitoring associated with these mines is detailed by Noller et al (1993), who also give details of current sampling and analytical methods employed by the NTDME. Data collected by the mining companies is also included in this interpretation, as it is considered reliable following many years of favourable intercomparison with NTDME check-monitoring results.

Field and laboratory measurements of electrical conductivity (EC) and pH have been both used, and where separate values for a single sample were available the mean has been used. Major cations and anions (electrical charges omitted for brevity), namely calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), bicarbonate (HCO_3) and sulfate (SO_4) were all obtained using standard methods. Due to the very low salinity of most surface water in the ARR, detection limits are important, and have been marked on some graphs. Some early data was measured with a detection limit of 1 mg/L, which is not sufficient for Ca, Mg, K and SO_4, and values of 1 mg/L on plots may represent maximum values prior to about 1985.

The important nutrients nitrate (NO_3), and to a lesser extent phosphorous (P) have been measured at most sites, but are not presented here. The data may be of limited use due to the detection limits used, but would still be likely to yield some useful insights into the nutrient status of the billabongs.

The data used here represent single samples from each water body. Various profiling studies have been carried out in many of the ARR billabongs, but few have been interpreted and published, and no attempt is made to do so here. Variation with depth tends to be more pronounced for some physico-chemical parameters, such as dissolved oxygen, than for pH, EC and the major cations.

3 Study Sites

Forty-five ARR sites in the NTDME water quality data base may be classified as pertaining directly to wetlands, along with a similar number of in-stream sites. The data set for each varies enormously, from one or two samples through to hundreds of samples over more than 20 years. Data from one site is presented in some detail, and some quick comparisons made to two others. The sites are, with their nationally registered site numbers and years of data, Gulungul Billabong (principal site, gs8210210, 1972–1994), Ja Ja Billabong (gs8210031, 1972–1989) and the Magela Floodplain outfall (gs8210019, 1975–1990; figure 1). None of these has been noticeably affected by mining activities, but all have been affected by other changes within the park such as the removal of most buffalo and in the cases of the two secondary sites, the invasion of the floating water weed *Salvinia molesta* (cf Skidmore 1990, Finlayson et al 1988 section 5.3.3).

A physical description of Gulungul Billabong and its underlying sediments is given by Nanson et al (1993). Walker et al (1984) considered it typical of backflow billabongs in the middle part of the Magela valley. Ja Ja Billabong is further downstream on the main Magela floodplain. Both billabongs were studied by Walker and Tyler (1984) and Walker et al (1994). The third site is the outfall of the Magela floodplain, which corresponds to site 5 of Murray et al (1993), and the last two sites were also studied by Hart et al (1987).

4 Results and Discussion

4.1 Gulungul Billabong

Figure 2 shows the full record of EC and pH from Gulungul Billabong, and the monthly variations obtained by plotting all values according to their position within whichever year they were taken. Figures 3 and 4 show the equivalent plots for major cations, and figures 5 and 6 for anions.

As established by earlier workers, there is a distinct seasonal cycle of salinity which is reflected in the EC record, with highest values being recorded towards the end of the dry season or in the early wet season. This is followed by a sharp fall when flow commences in Gulungul Creek that feeds the billabong, or in Magela Creek which may overflow back into the billabong. Minimum EC values are under 20 μS/cm, while the maximum EC recorded varies by a factor of nearly three between years, from about 100 μS/cm to over 250 μS/cm. The freshening of the billabong occurs between late November through to January, but most commonly in December. Sodium, potassium and chloride ions show the same general pattern, which is indicative of evaporative concentration. The pH shows no such distinct trend, but maintains a median value of about 6 throughout the year. It is quite variable, ranging from about pH 4 to over pH 9, with that full range apparent in the months of September and October.

Calcium values are low in the billabong, with many early measurements below a detection limit of 1 mg/L. When more sensitive analytical techniques were introduced in 1978 more meaningful data were obtained, showing a weak trend of increasing values as the dry season progresses. The range measured is from <0.1 to about 2.5 mg/L. Magnesium values are higher, ranging from 0.2 to over 5 mg/L. As with calcium, there is only a weak trend for higher values as the dry season progresses. Bicarbonate tends to be highest in the dry season, but can range from <5 to nearly 25 mg/L in the late dry season on different years. Many sulfate readings are below the early detection limit of 1 mg/L, with a tendency for higher values in at the end of the dry season, although there are some outliers. All sulfate values are less than 9 mg/L.

4.2 Ja Ja Billabong and Magela Floodplain outflow

Similar graphs to figures 2 to 6 were prepared for Ja Ja Billabong and the Magela Floodplain outflow, but are not presented here.

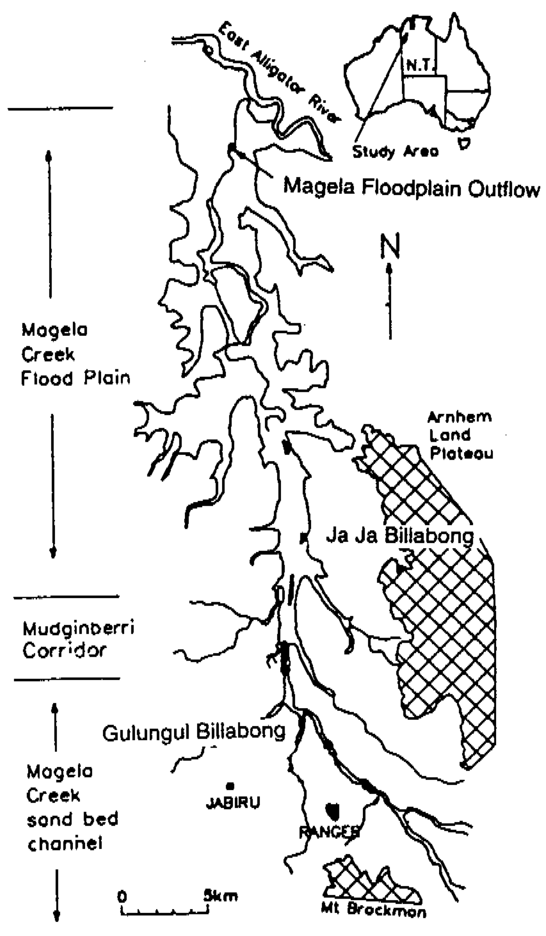

Figure 1 Location map (after Murray et al 1993)

Ja Ja Billabong show similar variations to Gulungul Billabong, with similar minimum EC values and slightly higher maximum EC values, up to 380 µS/cm. High values are more likely to persist until January. This is consistent to its position further downstream than Gulungul, and that it has little catchment area of its own. The pH shows a more established annual pattern, with higher values (around 6) from March to August, falling to 4 to 5 in December and January. Major cations and anions show similar patterns to Gulungul Billabong, with higher maxima as expected from the higher EC maxima.

The data record for the Magela Floodplain is not as comprehensive as those of the two billabongs discussed. The site is usually dry in October and November. The range of EC is much greater, ranging from 10 to 17 000 µS/cm. The high values reflect intrusion of seawater (about 42 000 µS/cm) late in the dry season or early in the wet season before floodwaters reach the site, and have been recorded between October and January. The maximum pH is similarly high, reaching the seawater value of 8.4 on occasions. The EC during the flooded period is generally about 50 µS/cm in January and February, rising to nearly 1000 µS/cm late in the season (this may incorporate a minor component of seawater). The pH during flooding is about 6, but has been recorded as low as 4.1 and may reach 7 or greater by the middle of the year.

All cations show and increasing trend, and when seawater intrusion is excluded rise from about 1 mg/L (all cations) to about 10 mg/L for both calcium and magnesium, about 40 mg/L sodium and 12 mg/L potassium. Chloride and to a lesser extent bicarbonate mirror sodium and potassium, but sulfate values are very low except in the months of September, December and January, with three very much greater values recorded in the middle months of the year apparent.

5 Summary and Conclusion

Gulungul and Ja Ja Billabong show similar annual patterns of the physico-chemical parameters examined, with minimum values of EC, Na, K, and Cl early in the wet season, increasing due to evaporative concentration over the dry season. A similar but less definite pattern occurs with Ca, Mg and SO_4. Bicarbonate is quite variable with a weak tendency to be higher in the dry season. The maximum values of all these parameters tend to be higher in Ja Ja Billabong. The pH in Gulungul has a median of about 6 all through the year, and while that in Ja Ja is similar for most of the year it usually falls to 4 to 5 in December and January.

The general pattern at the outlet of the Magela Floodplain is similar to the upstream billabongs, although evaporative concentration of EC and the anions and cations is much more pronounced. The pattern is greatly modified by the occasional intrusion of dilute seawater from the East Alligator estuary, with the highest recorded EC about 40% of the seawater value.

The NTDME water quality data base is a valuable deposit of both background and mine-affected physico-chemical data for wetlands and streams of the Alligator Rivers Region for over 20 years at some sites. It has great potential to add to the basic understanding of the natural wetland and riverine environments of the Region, as well as the limited impact of the two mines in their immediate neighbourhoods.

6 Acknowledgments

The data on the NTDME water quality data base represent an enormous sustained effort by the companies involved and the Northern Territory authorities, both the NTDME and the Power and Water Authority, and the predecessors of both. This paper was presented with the permission of the Director, NTDME Environment Division. Thanks to Alison Woods for editorial assistance.

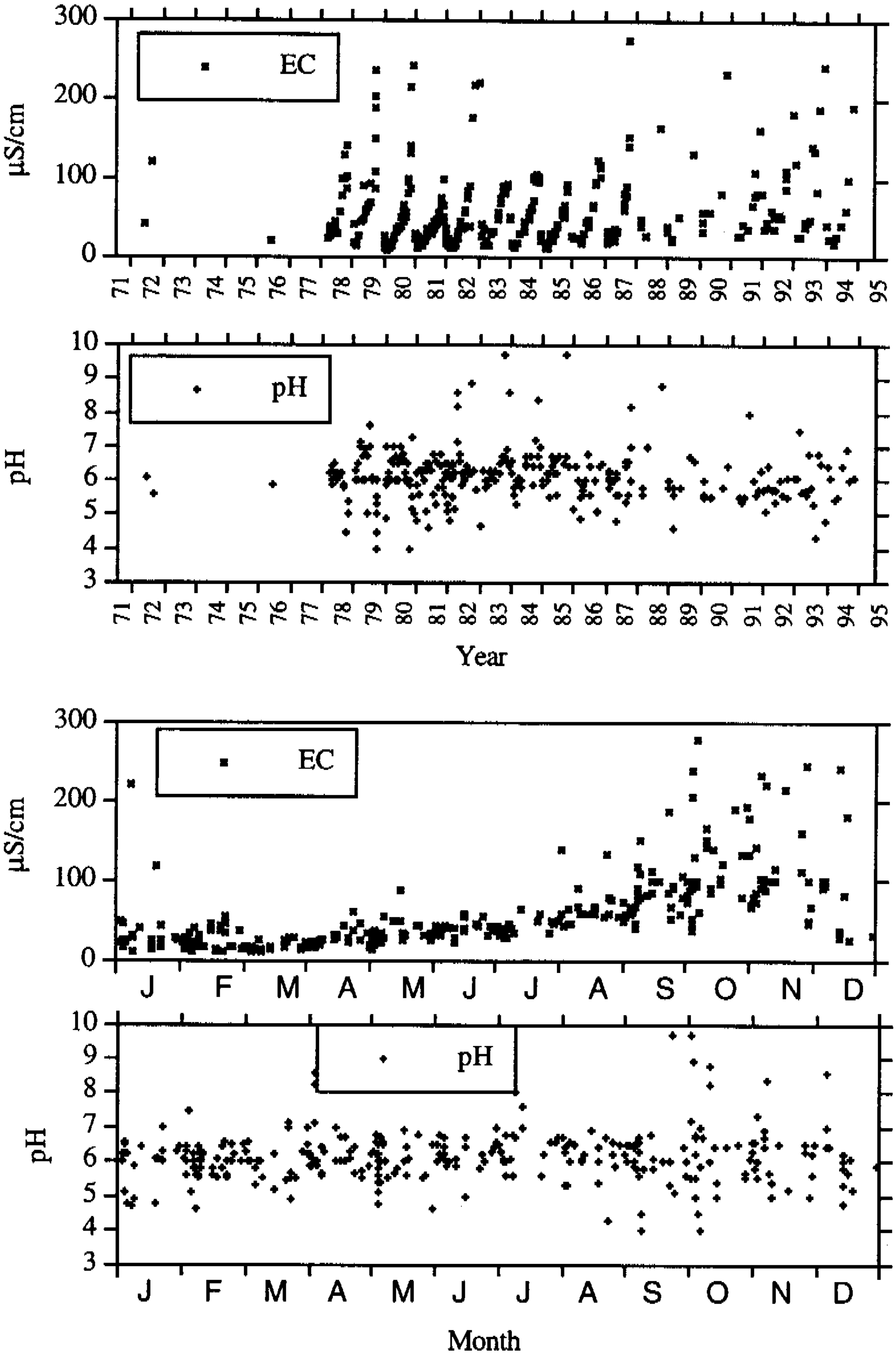

Figure 2 Historical record and monthly variation of electrical conductivity (EC) and pH at Gulungul Billabong

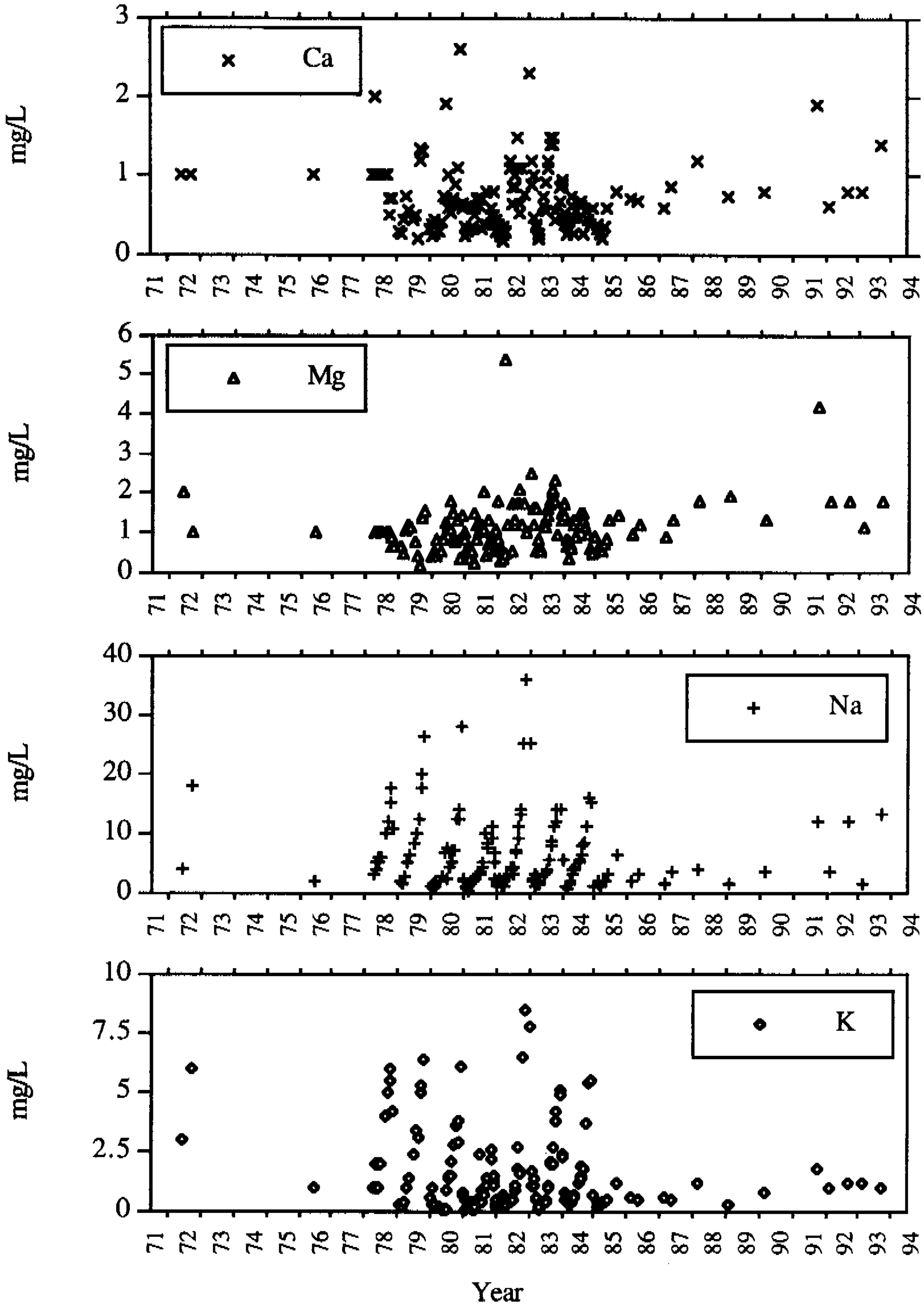

Figure 3 Historical record of major cations at Gulungul Billabong

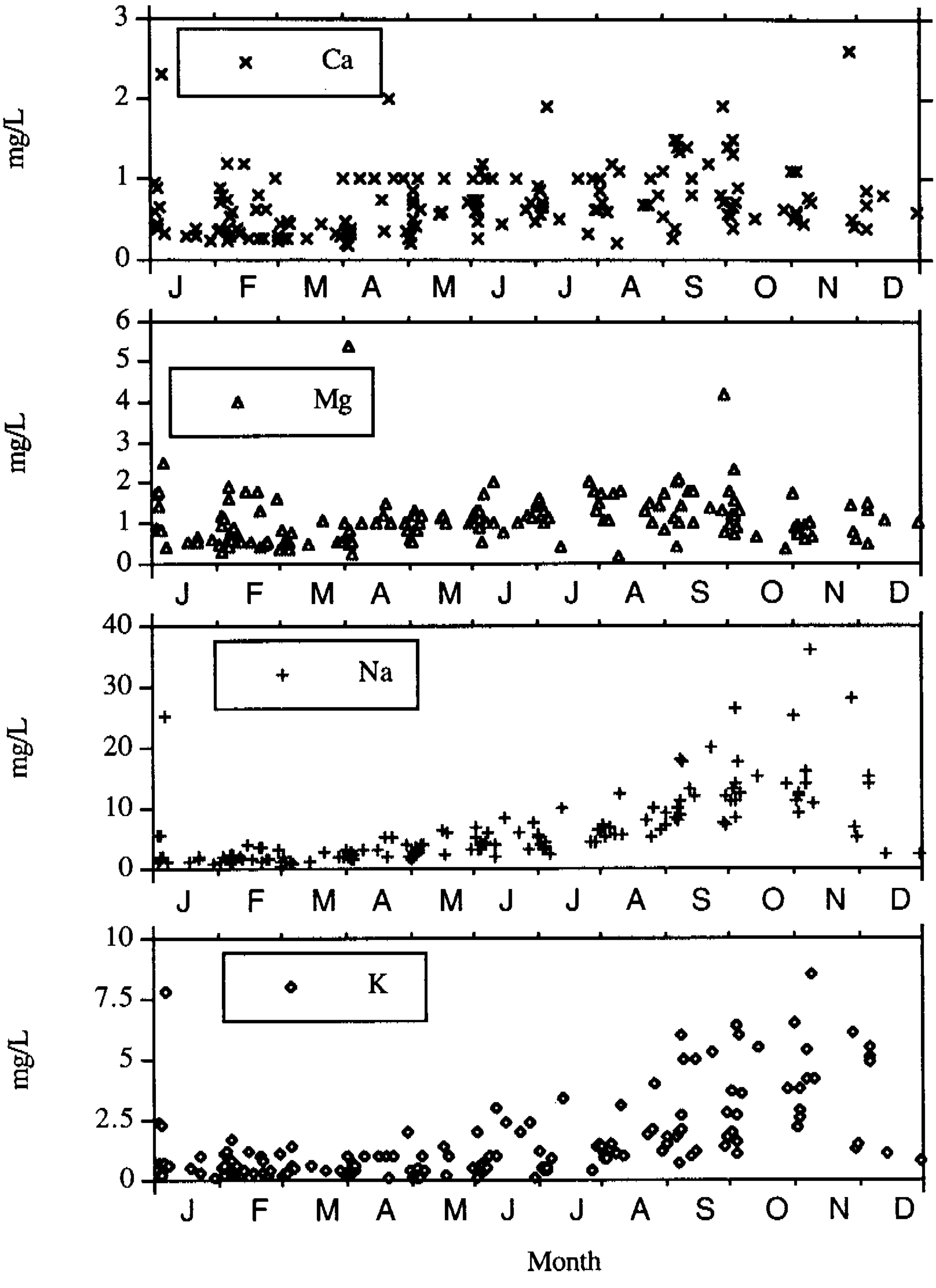

Figure 4 Monthly variation of major cations at Gulungul Billabong

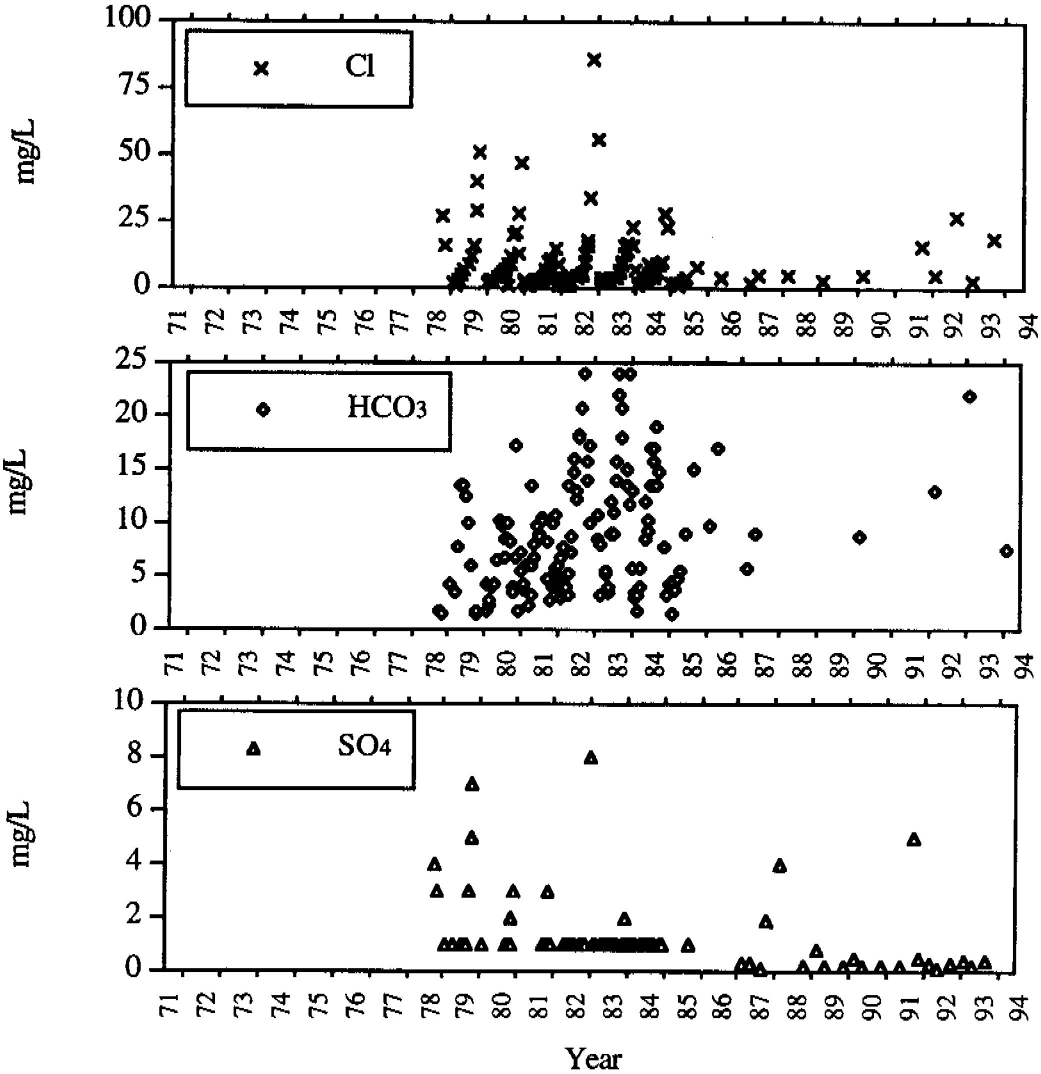

Figure 5 Historical record of major anions at Gulungul Billabong

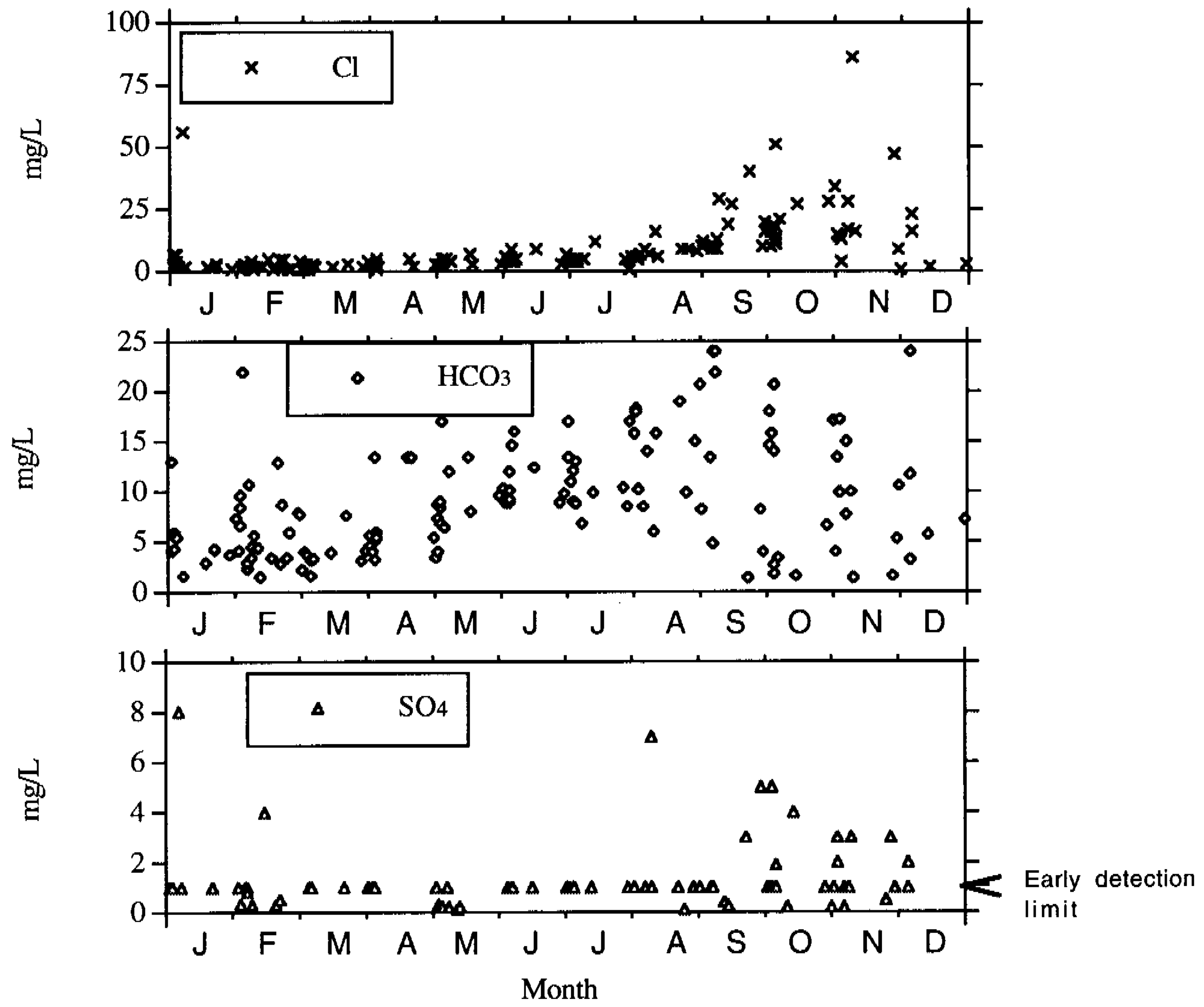

Figure 6 Monthly variation of major anions at Gulungul Billabong

7 References

ANPWS 1989. Visitors Guide, Kakadu National Park. Pamphlet RW/402/ANPWS, Australian National Parks and Wildlife Service.

Christian CS & Aldrick JM 1977. *Alligator Rivers Study - A review report of the Alligator Rivers Region environmental fact-finding study.* AGPS, Canberra.

Davy DR & Conway NF 1974. Environmental studies Northern Territory uranium province 1971/73. In *The Alligator Rivers Area Fact Finding Study Four AAEC reports*, Conway NR Davy DR Giles MS Newton PJF (ed) & Pollard DA AAEC/E305, Australian Atomic Energy Commission, Lucas Heights, III–1 - III–71.

Finlayson CM, Bailey BJ, Freeland WJ & Fleming MR 1988. Wetlands of the Northern Territory. In *The Conservation of Australian Wetlands*, (eds) AJ McComb & PS Lake, Surrey Beatty & Sons, Sydney, 103–126.

Fox RW, Kelleher GG & Kerr CB 1977. *Ranger Uranium Environmental Inquiry, Second Report,* AGPS, Canberra.

Hart BT & McGregor RJ 1980. Limnological survey of eight billabongs in the Magela Creek catchment, Northern Territory. *Australian Journal of Marine and Freshwater Research* 31, 611–626.

Hart BT, Ottaway EM, & Noller BN 1987. Magela Creek system, northern Australia. I. 1982–83 Wet-season water quality. *Australian Journal of Marine and Freshwater Research* 38, 261–288.

Murray AS, Johnson A, Martin P, Hancock G, Marten R & Pfitzner J 1993. Transport of naturally occurring radionuclides by a seasonal tropical river, northern Australia. *Journal of Hydrology* 150, 19–39.

Nanson GC, East JT & Roberts RG 1993. *Quaternary Stratigraphy, Geochronology and Evolution of the Magela Creek Catchment in the Monsoon Tropics of Northern Australia.* In *Sedimentary Geology,* Vol. 83, pp. 277–302.

Needham RS & De Ross GJ 1990. Pine Creek Inlier - regional geology and mineralisation, In *Geology of the Mineral Deposits of Australia and New Guinea*, (ed) FE Hughes, The Australasian Institute of Mining and Metallurgy, Melbourne, 727–737

Noller BN, Woods PH, & Milne FJ 1993. *Sampling and preservation of surface and groundwaters at Northern Territory sites for general and trace analysis.* Internal Report (Environmental) 93/1, Northern Territory Department of Mines and Energy, Darwin.

Skidmore JF 1990. Human impact on the Alligator Rivers Region. In *Proceedings, Workshop on Biological Toxicity Testing as a Regulatory Mechanism*, Darwin & Jabiru 4–7 September 1989, (eds) RA McGill & KA Malatt, Northern Territory Department of Mines and Energy, Darwin, 147–164

Walker TD & Tyler PA 1982. Chemical characteristics and nutrient status of billabongs of the Alligator Rivers Region, NT. Open file record 27, Supervising Scientist for the Alligator Rivers Region, Canberra. Unpublished paper.

Walker TD, Waterhouse J & Tyler PA 1984. Thermal stratification and the distribution of dissolved oxygen in billabongs of the Alligator Rivers Region, NT. Open file record 28, Supervising Scientist for the Alligator Rivers Region, Canberra. Unpublished paper.

Woods PH, McGill RA, & Noller BN, 1994. Water, soil and sediment monitoring programs; some lessons from 15 years' experience in the Alligator Rivers Region, Northern Territory, Australia. In *Proceedings, Australasian Institute of Mining and Metallurgy, 1994 Annual Conference,* Darwin, 5–9 August 1994, AusIMM Publication Series No. 5/94, 437–440.

THE ROLE OF WETLANDS IN CONTROLLING CONTAMINANT DISPERSION FROM MINE WASTE WATERS

BN NOLLER

Environment Division, Department of Mines and Energy,
GPO Box 2901, Darwin, NT 0801

ABSTRACT

The annual wet season in the tropical zone produces runoff on mine sites which may become more contaminated from mineral processing and contact with waste rock. Waste water runoff may be discharged offsite and reach downstream aquatic ecosystems, including wetlands. In many cases constituents are diluted or ameliorated through adsorption and co-precipitation processes. Acidification may have deleterious effects on biota, making it difficult to restore the aquatic ecosystem. Wetlands are most suited to handling the recessional flows associated with the end of the wet season in contrast to high dilution achieved during discharge into flood episodes. Wetlands can minimise the dispersion of contaminants through retention by aquatic plants and their associated sediment/soil. The fringe zones of major wetland areas can also be utilised to protect the main area of the wetland itself.

The composition and kind of waste water determines the types of wetland systems to be employed. The waters which are commonly found in tropical Australia are: (i) mildly alkaline waters, (ii) neutral surface runoff waters, and (iii) acidic waters which arise from the acid mine drainage process. The techniques which can be used for mine waste water amelioration are: (i) using existing wetlands, (ii) enhancement of existing wetland systems, and (iii) incorporation of specific water treatment zones such as the use of constructed zones for acid drainage.

Wetlands can thus be considered as a means of achieving environmental control of waste water from mining in the tropical zone.

Keywords: wetlands, tropical zone, mining, contaminant control, waste water.

1 Introduction

Northern Australia lies within the wet-dry tropical zone and experiences an annual wet season (Butterworth 1994). Following the initial rains, runoff waters saturate the soil layer and begin to accumulate on mine sites. Contact of mine processing materials and waste rock with rainwater leads to the incorporation of contaminants into runoff. Following overflow, downstream aquatic ecosystems may be affected if overflows of waste water occur.

Aquatic plants are known concentrators of heavy metals and other elements and their forms which are found in mine waste waters. The concentrating ability of aquatic plants far exceeds that for terrestrial plants (Outridge & Noller 1991). In addition to concentrating trace elements from water, aquatic plants may be used to trap suspended sediments. Following senescence, plant material becomes incorporated into sediment.

There are two main ways in which mining projects can utilise wetland systems. These are: (i) to minimise the dispersion of waterborne contaminants, and (ii) to utilise the fringe zones of existing wetlands to protect the main area of the wetland.

This paper seeks to categorise the kinds of wetland applications against water quality for mining activities in the tropical zone of Northern Australia.

2 Annual climatic cycles

The annual wet season in northern Australia can be summarised in terms of the average monthly rain days (Butterworth 1991). The highest number of rain days occurs between November and April, reaching a maximum average of 21 days in Darwin, whilst the lowest number, during May-October, falls to an average of near zero for June–August (Butterworth 1991). Wetlands are passive devices and are therefore best suited to handling the recessional flows associated with the end of the wet season, corresponding to the period when the average number of rain days decreases markedly. Thus they are suitable buffers against the effects of more concentrated waters on downstream aquatic ecosystems following authorised releases of mine waste waters. During the middle of the wet season from January-March, waste water from mining is best disposed of by discharge into episodic floods because high dilutions are achieved. Wetlands therefore have a beneficial role in handling the recessional flows from mine sites which generally have constituents at more concentrated levels and can be more damaging to downstream aquatic ecosystems.

3 Classes of mine waste waters

Contaminants in mine site runoff arise from solutions associated with mineral processing residues and waste rock. These can be grouped into three main classes:

3.1 Mildly alkaline waters

These waters are usually bicarbonate-rich and derived from groundwater which has contacted carbonate minerals. A common source is pit dewatering (Noller et al 1994). Seepage from carbonate-containing waste rock material may also produce mildly alkaline runoff. Highly alkaline waters accompanying cyanide leaching or bauxite dissolution are not generally released unless highly diluted. Wetlands at tropical locations are able to absorb low concentrations of cyanide and its breakdown products (nitrate/nitrite and ammonia) because low levels of cyanide are a nutrient source.

3.2 Near neutral waters

These waters arise primarily from surface runoff which has ponded and contains little addition of dissolved constituents. Elevated levels of suspended solids may be present and be the primary potential pollutant of any released water.

3.3 Acidic waters

Acidic waters, not specifically associated with mineral processing, arise from the acid mine drainage process. This process is the oxidation of mineral sulfides, primarily pyrite, by air and water to give sulfuric acid. The acid produced may enhance the dissolution of other sulfide and gangue minerals and lead to the presence of elevated concentrations of a whole range of metals in solution, apart from iron. Sulfate is the dominant anion. Acid mine drainage is usually accompanied by extensive downstream coating of stream sediments by freshly precipitated hydrated ferric oxide, having a bright yellow-orange colour.

4 Classes of wetlands

Wetlands for the amelioration of mine waste waters can be categorised into various classes. These are as follows:

(i) Existing wetlands

(ii) Enhanced existing wetlands

(iii) Specific water treatment zones or constructed zones for extreme acid or alkaline conditions, incorporated into artificial wetlands.

The essential difference between (iii) and the previous two classes is the specific need to incorporate special treatment zones which successively modify the waste water and give an improvement in water quality.

5 Fundamental processes in constructed wetlands

The key to achieving optimum performance of a constructed wetland system is through the incorporation of the fundamental processes in the treatment zones in the specific order necessary to give the desired change in water quality (Machemer et al 1993). The fundamental processes which may need to be taken into account are as follows:

- The presence of organic matter giving removal of arsenic, uranium, and other heavy metals
- Iron oxides playing a key role in the fixation of heavy metals and arsenic
- Limestone in the acid neutralising zones which is consumed and needs to be replaced following consumption
- High dissolved iron concentration causing a decrease in active limestone material
- Organic-rich material reducing sulfate to sulfide in the presence of appropriate bacteria

The specific order of utilising these processes is determined by the kind of waste water to be treated. For example, in the case of acid drainage water, a plan for a wetland with constructed zones would include the following processes in the order selected, as follows:

- Treat the acid drainage waters emerging from the waste rock dump by allowing it to flow over an open riffle surface of wide surface area. This action enables surface oxidation of soluble iron to occur and gives effective removal of iron from solution.
- Direct 'oxidised' waters into a below-surface organic-rich/limestone zone with air excluded, creating reducing conditions capable of reducing sulfate to sulfide and removing heavy metals as insoluble sulfides. The closer to neutral pH, the more easily the reduction of sulfate is achieved (Batal et al 1990).
- Pass exit waters from the 'reducing' zone to the aquatic plant zone with meanders in order to give maximum contact of waters with the living plants and associated organic matter. The area of aquatic plants should be as large as possible.

Such a scheme enables zones to be linked in the constructed wetland in a manner that will ensure the continual improvement of the waste water quality. Aquatic plants will not, in general, tolerate direct contact with strongly acidic waters. There needs to be a flow pathway through or around wetland systems for flood waters so that excess waters do not spill over into the wrong places and cause other damage. Alternative flow through trenches containing limestone may need to be constructed which will allow for treatment of runoff at high flow rate.

6 Features of aquatic plants and natural wetlands

There is very little information available about the application of tropical aquatic plant species to wetland systems for waste water treatment. For example, where existing wetlands and enhancement of the existing wetlands have been used, locally occurring species have been incorporated or their growth enhanced. In the case of mine dewatering, a number of observations of invasion by *Typha* sp. have been observed, (Noller et al 1994); this species flourishes in the presence of flowing water.

A number of observations can been made as follows:

- The species *Typha* sp., *Eleocharis* sp. and *Sclera poaliformis* are able to grow in and tolerate acid water, down to pH 3.
- There is little data on the suitability of any other tropical species for wetland systems at mine sites.
- It is possible to achieve high density of plants in wetland systems.
- Growth proceeds with increasing water depth to a maximum depth which may vary between different species.
- Aquatic species need to survive the annual cycle through to the end of the dry season and be rejuvenated or grow from seed when the wet season recommences.

7 Conclusion

Wetlands are a means of achieving environmental control of waste water from mining but their utilisation is in a state of infancy in the tropical zone.

8 References

Batal WA, Laudon LS, Wildeman TR & Mohdnoordin N 1990. Bacteriological tests from the constructed wetlands of the Big Five Tunnel, Idaho Springs, Colorado. *Chapter 38h in Constructed Wetlands for Wastewater Treatment; Municipal, Industrial and Agricultural,* (eds) DA Hammer, Lewis Publishers, Michigan, 48118, 550–557

Butterworth I 1994. The tropical climate: humidity, storms and lightning. In *Proceedings of Seminar Darwin, Australia 13–15 November 1991 Power supply and maintenance of scientific instruments in the tropics,* (eds) J Webb & B Noller, Murdoch University, Western Australia 6150, 1–12.

Machemer SD, Reynolds JS, Laudon LS & Wildeman TR 1993. Balance of S in a constructed wetland built to treat acid mine drainage, Idaho Springs, Colorado, USA. *Applied Geochemistry* 8, 587–603.

Noller BN, Woods PH & Ross, BJ 1994. Case studies of wetland filtration of mine waste water in constructed and naturally occurring systems in Northern Australia. *Water Science and Technology* 29 (4), 257–265.

Outridge PM & Noller BN 1991. Accumulation of toxic trace elements by freshwater vascular plants. *Review of Environmental Contamination and Toxicology* 121, 1–63.

WETLAND FILTRATION RESEARCH AT ERA RANGER MINE

H NISBET

Rehabilitation Officer, ERA Environmental Services Pty Ltd,
PO Box 39443, Winnellie, NT 0821

ABSTRACT

Natural and constructed wetland systems are becoming a significant component of Ranger's water management and environmental monitoring program. Research has been directed towards wetland filtration as a method of polishing mine run-off water prior to release into the Magela Creek, using both the billabong systems and natural drainage areas plus constructed wetlands.

Wetland areas have been created within the mine in the form of stockpile drains and settlement ponds (retention ponds and others) and trial wetland filter systems. Experimental release of mine water through these wetlands has given a good indication of system capabilities, both hydrological and chemical. Chemical and toxicological analyses have shown a marked improvement in water quality after passing through these created wetland systems, as well as natural billabong systems. Research into the key mechanisms involved in the process of polishing mine water has yielded information on suitable design for the development of artificial wetlands, including appropriate locations, flow designs, and vegetation establishment techniques.

Ranger will continue to research both the natural and constructed wetlands within the vicinity of the mine. Research will expand in the future in order to increase the role of this technique in site water management during the operational phase as well as for long term passive water treatment following construction of the rehabilitated landform.

1 Introduction

ERA Ranger Mine, located at Jabiru, 230 km east of Darwin mines uranium by open cut methods. Rainfall run-off from the mine pit and process plant, ore stockpiles (>0.02% U) and other designated areas, is directed into Retention Pond 2 (RP2), within the Restricted Release Zone (RRZ). Wetland areas within the mine area include; natural wetlands, these are Coonjimba, Djalkmarra and Georgetown Billabongs, and their associated creeks; and constructed wetlands, including the mine drains and sediment settling ponds at the base of stockpiles, retention ponds (1 and 4), a simple wetland filter system constructed downstream of RP4 and the RP1 wetland filter (figure 1).

ERA has managed to avoid releasing RRZ water into the Magela Creek by spray irrigating a 55 ha area of woodland adjacent to the mine. With the increase in area of stockpiles within the RRZ and a large 1994–95 wet season, ERA had a significant excess of water which was stored in RP2 and the pit. This water will need to be disposed of prior to the next wet season. Disposal alternatives are under review and will be resolved via discussion with the authorities, including representatives of the Aboriginal land owners. Treatment is likely to use wetland filtration followed by spray and flood irrigation. Wetland filters will be monitored and researched in order to gain more information about the criteria for the most suitable design for the development of larger systems to cope with the increasing demand for water treatment.

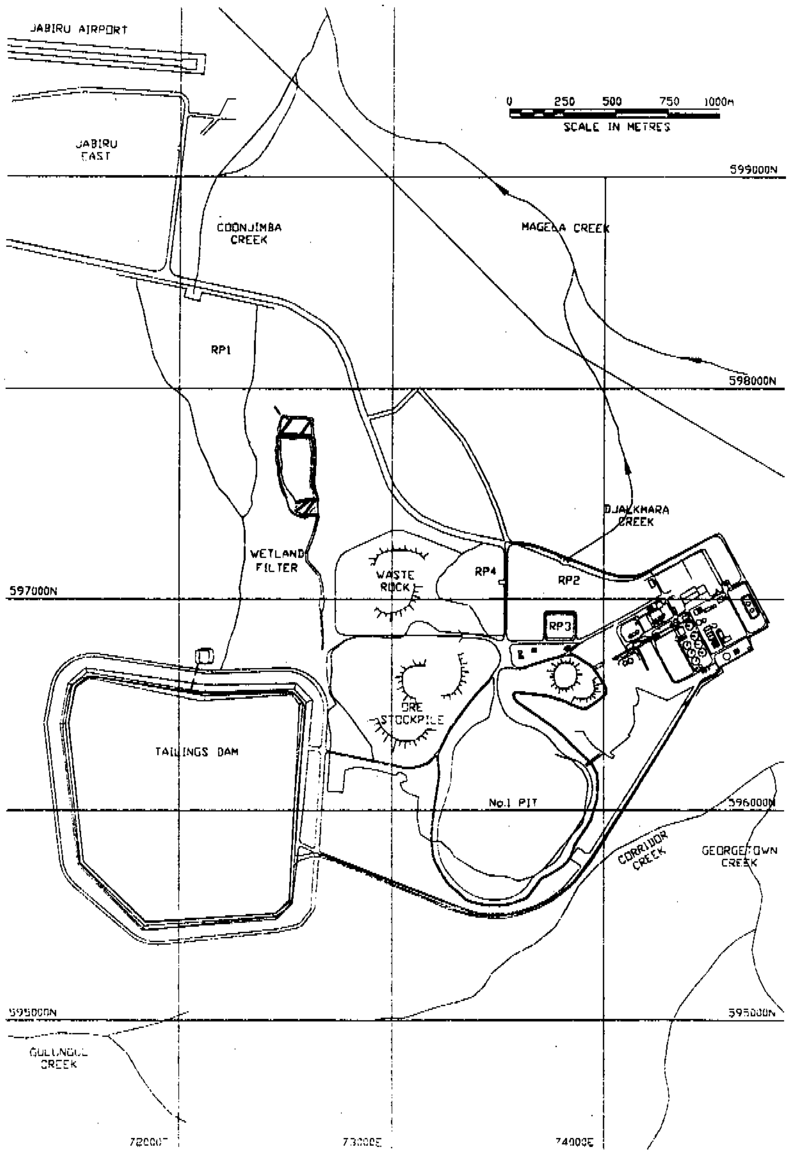

Figure 1 Water management system at Ranger showing the location of natural and artificial wetlands

2 Research into wetland processes at Ranger

Research on wetland processes have been carried out at Ranger for almost 10 years. Fitzpatrick et al (1986) investigated a brown precipitate floating on RP4. Analysis showed the substance to be a precipitate of ferrihydrite and lepidocrocite associated with the water plant *Ultricularia* *muelleri* plus various algae and bacteria. The precipitate is composed dominantly of Fe_2O_3 (59.3%). Significant quantities of heavy metals were present in the precipitate including uranium, cadmium, lead, vanadium and manganese.

Taylor (1987) carried out investigations in response to higher than usual levels of uranium in RP2 and RP4. This work outlined a possible method of removing uranium using the mineral magnetite (iron oxide mineral). Using this technique the pH of the water can be adjusted so that the charge on the surface of the magnetite crystallites is either positive or negative in order to absorb anionic or cationic pollutants. The magnetite with adsorbed pollutants is then removed from the water by sedimentation or an applied magnetic field. By changing the pH, the adsorbed species can then be released from the magnetite into a controlled environment.

In 1987–88 the ERA Environment Department planted wetland vegetation in a series of trenches close to the NW seepage collector of the tailings dam (Ranger Uranium Mines 1987–1988). The experiment identified local species useful for wetland filtration and investigated establishment techniques. Both parallel and zigzag trench systems were constructed. These were planted with *Typha, Eleocharis* and *Eucalyptus camaldulensis*. One system received water pumped from the seepage collector. Results showed that it was possible to successfully transplant both *Typha* and *Eleocharis* with evidence of growth by the end of the season.

In late 1989 and early 1990, the CSIRO Minesite Rehabilitation Research Group carried out a survey to determine whether natural or artificial wetlands significantly modified the mobility of contaminant elements from the mine (Beech et al 1990). Sites were established in drains at the base of the stockpiles and on the shoreline of RP4. Samples of sediments, vegetation and water were collected in the late dry season and the following (mid) wet season. This work highlighted the differences in element concentration between drainage systems, sampling sites, sampling times, plant species and plant tissues.

3 Experimental wetland filters at Ranger

During the 1989/90 wet season, Ranger carried out an experimental release of RP4 water through an area of land modified to act as a wetland filter (figure 2). The trial was conducted in two parts. In the first, water was retained in the system for three days, in the second the water flowed through the system for 3 days. The discharge water eventually flowed to Djalkmarra Billabong and then into the Magela Creek. Solute attenuation was estimated using water quality and hydrological data (Ranger Uranium Mines 1990a). The following results were obtained:

- magnesium, sulfate and uranium were attenuated in significant quantities
- manganese was variable and at times higher than RP4 suggesting that the wetland added manganese to the system
- calcium was approximately 30% higher than in RP4 which may have come from calcium containing minerals in the soil (calcite, gypsum, dolomite)
- toxicity tests carried out using Cladoceran showed a decrease in toxicity from 10% in RP4 to >20% (No Observed Effect Concentration) in waters collected after wetland filtration (Ranger Uranium Mines 1990b)

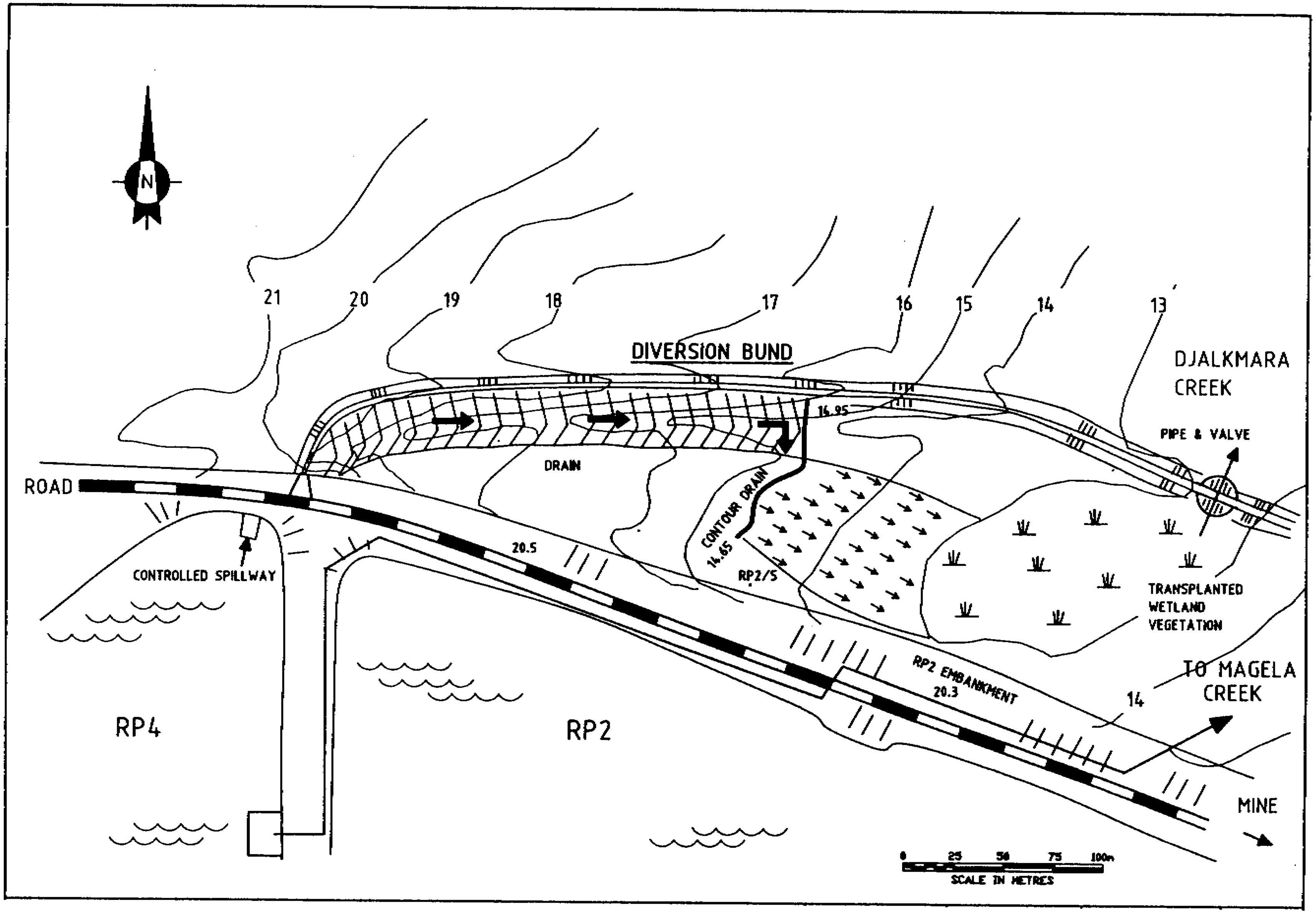

Figure 2 Constructed wetland downstream of Retention Pond 4 (RP4)

Following this research it was decided to construct a wetland filter in the NE section of the RP1 catchment, close to the northern waste rock dump and tailings dam. The purpose was to conduct a trial using run-off from the Very Low Grade (VLG) stockpile (0.02-0.05% U), representing the best quality RRZ water. The site chosen made use of a borrow pit used for the 1989/90 tailings dam wall uplift. The area was not considered ideal in that it is not subject to seasonal inundation and much of the clay was removed. The system, designed in liaison with the CCNT and CSIRO, was built in 1990 (figure 3). The filter was divided into compartments by semi-permeable bunds with overflow spillways. The southern experimental end receives channelled run-off from the waste rock dumps. This exits the final compartment to enter a central lake and finally overflow into RP1. The northern end receives run-off from the woodland and represents a control. Modifications were made in 1991 with assistance from the CCNT (Jonauskas & Sterling 1992) to provide more freeboard on bunds, designed concrete inlet and outlet flumes, gauging stations and spillways for the internal bunds.

At the onset of the wet season rains, the filter walls were hydromulched with grass and tree seed. The Australian Trust for Conservation Volunteers (ATCV) assisted in transferring *Eleocharis, Cyperus* and *Valisneria* from billabongs and *Typha* from RP4. These were planted at a spacing of one metre at the base of all the filter walls. Tubestock were planted at a one metre spacing along the walls. *Azolla pinata* (a floating fern) was collected and transferred in buckets. Water lilies were transplanted from RP1. Further advice on the propagation of wetland plants was sought from the CSIRO (Pistillo 1991).

During the 1993–94 wet season the system was left for vegetation to establish. Hydrological chemical and toxicological monitoring of waste rock run-off moving through the system was carried out during the season. Unidata loggers were installed at the site stations to record stage height of inflows and outflows. Automatic water samplers were set up to target specific hydrological events. Rating curves were calculated to relate measured flow height to flow volume. Results of this monitoring showed.

- uranium and sulfate concentrations remained similar between the inlet and outlet (sometimes higher at the outlet). This was also the case for the control section suggesting a flushing from the internal bunds.
- manganese levels at outlet were 1/3 of those at inlet levels
- turbidity was reduced by large amounts during storm events
- sodium, potassium and calcium remained fairly constant
- pH was consistently brought to neutral

Until this stage the levels of contaminants entering the filter had been low, being run-off from the general catchment and waste rock. It was necessary for ERA to seek application to pass poorer quality water through the system to make any kind of assessment of its capability. In July 1994 approval was given to pass RP2 water through the system as long as it was contained within the central lake where it was to evaporate or be pumped back into RP2.

The experiment was designed to collect critical physical, chemical and biological information from the wetland before, during and after the trial. The goal of the experiment was to have reliable mass balances for the required solutes. This required hydrological data collection to develop flow rates and comprehensive water quality data.

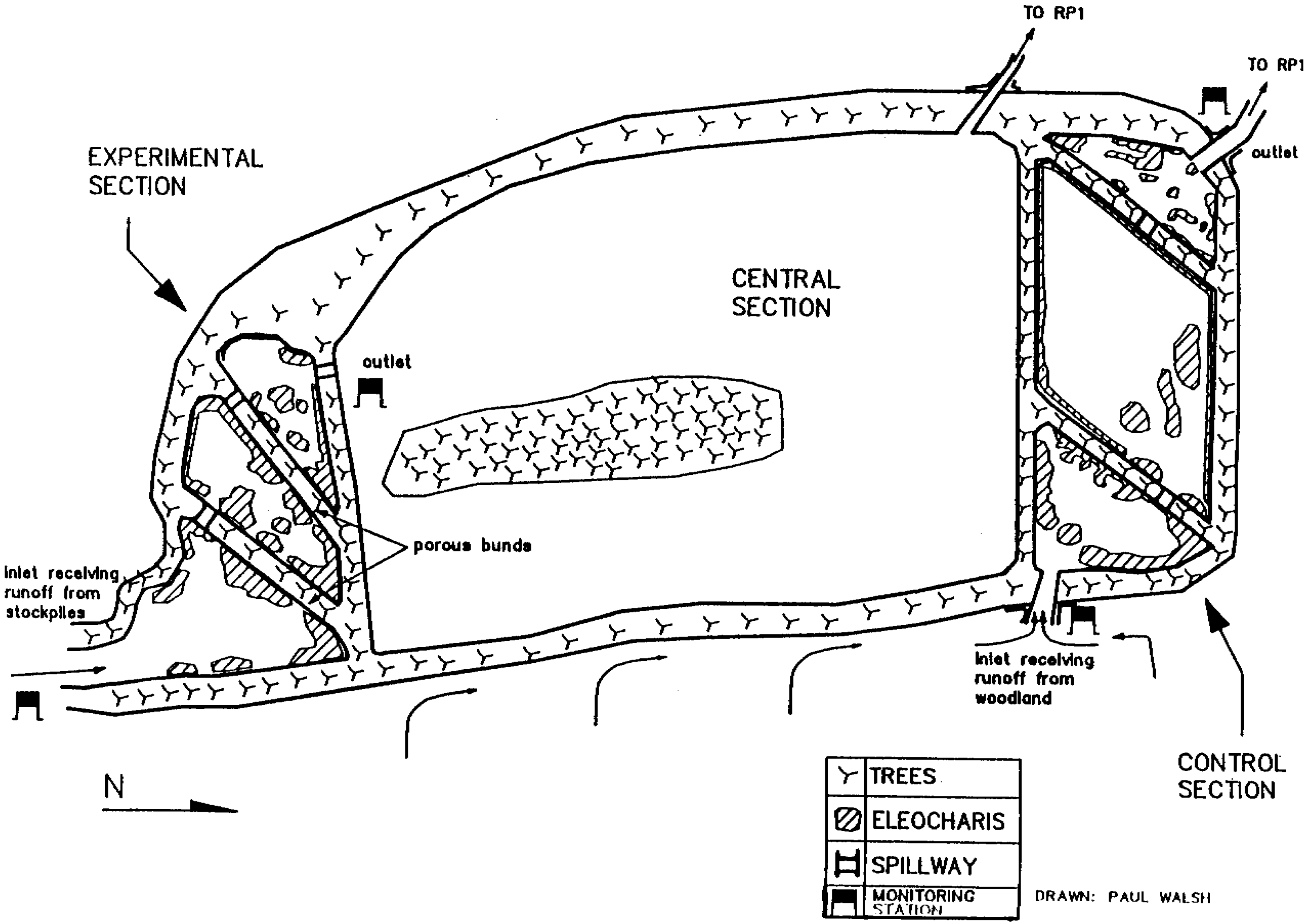

Figure 3 RP1 Wetland filter system

Additional data on the chemical composition of plants and sediments were collected before, during and after the trial in order to determine the partitioning of the solutes in the different sections of the system. Residence time and flow pathways were measured by an injection of a dye tracer once the system reached steady flow. Approximately 20 000 cubic metres of RP2 water was pumped into the system. The results from this experiment are currently being analysed and reported by the CSIRO, however the water chemistry results highlight some of the major points of interest:

- uranium levels were markedly reduced after passing through the wetland. Levels of 1000 µ g/L uranium recorded at the inlet drain were reduced to less than 200 µg/L at the outlet and to less than 50 µg/L at the central lake.
- sulfate levels of 700–800 mg/L were recorded at the inlet, and remained reasonably consistent through each of the compartments, with a final increase to levels of 2000 mg/L in the central lake.
- magnesium levels recorded as 200 mg/L at the inlet and the outlet.
- conductivities were recorded as 1500 µs/cm at the inlet and outlet, as expected from the magnesium and sulfate levels remaining consistent.
- pH changed from 7.5 - 8.5 in the inlet to generally lower at the outlet (6.9–7.5).

Following this experiment ERA carried out a further sampling program in the 1994–95 wet season to test for remobilisation of contaminants into RP1 at the onset of the wet season rains. The wetland cells were half full in early January when the first monsoonal storms arrived. Water samples were collected at this time, during overflow and for a further few weeks at lesser frequencies. The results from this work are also to be reported by CSIRO however a brief look at the water chemistry results reveal:

- uranium levels recorded in the inlet, outlet into central lake and outlet from lake to RP1 remained consistently low ~ 20–50 µg/L at each of the sites with an isolated recording of 180 mg/L at the wetland outlet. This result is likely to be due to some flushing however it is low when considering the original levels of U(1000 g/L) entering the system in the RP2 water.
- sulfate and magnesium were much reduced from that recorded in the initial experiment with no real sign of an initial flush. Sulfate levels were recorded as 120-220 mg/L, and magnesium as 30–75 mg/L at the wetland outlet.

4 Future directions

ERA is planning to utilise the RP1 trial wetland filter to treat excess water from the 1994–95 wet season. Modifications will be made to the present design in order to increase the capacity of the system by introducing a series of bunds across the central lake to force the water to take a longer, more meandering path. Further information from the monitoring of these releases will provide more of the basic design criteria to assist in developing systems in other catchments with the capacity for larger flows and poorer water qualities.

In the meantime, research involved in the processes occurring within the wetland filters will continue with assistance from the CSIRO, namely identification of the key solute removal processes, measurement of fluxes of dissolved and particulate forms of target solutes over seasonal cycles, and the adsorption capacity and tolerances of wetland plants (particularly algae) for target solutes.

5 References

Beech TA, Kimber RWL, Milnes AR, Moen R, Ragusa S, Reddell P, Rosbrook PA 1990. *Management of Very Low Grade Ore Stockpiles, Ranger Project Area.* CSIRO Minesite Rehabilitation Research Program, Adelaide.

Fitzpatrick RW, Self PG, McClure SG & Milnes AR 1988. *Scavenging of Heavy Metals by Natural Iron Precipitates in Retention Pond 4, Ranger Mine, Jabiru, NT. Focus Report No5,* CSIRO Minesite Rehabilitation Research Group.

Jonauskas PE & Sterling EA 1992. *Experimental Wetland Filter Overview.* Report to ERA Ranger Mine, The Conservation Commission of the Northern Territory, Darwin.

Pistillo P 1991. *Quantitative Investigations of Processes of Uptake or Transmission of Water-Borne Contaminants in a Constructed Wetland in the Catchment of RP1. Stage 1: Propagation of Wetland Plants.* CSIRO Minesite Rehabilitation Research Group, Adelaide.

Ranger Uranium Mines 1987–1988. *Environmental Monitoring Review Wetland Filter System,* ERA, Jabiru.

Ranger Uranium Mines 1990(a). Amelioration of Retention Pond Water by Wetland Filtration. Internal Report, Jabiru.

Ranger Uranium Mines 1990(b). *Biological Screening of Retention Pond Waters*, ERA, Jabiru, Environmental Annual Report.

Taylor RM 1987. *Potential Uranium Removal from Retention Ponds, Focus report No 2 to Ranger Uranium Mines.* CSIRO Minesite Rehabilitation Research Group, Adelaide.

POPULATION BIOLOGY OF *BUFO MARINUS* IN NORTHERN AUSTRALIA

RA ALFORD, MP COHEN, MR CROSSLAND, MN HEARNDEN & L SCHWARZKOPF

Department of Zoology, James Cook University, Townsville, Qld 4811

ABSTRACT

*Cane Toads (*Bufo marinus*) spread through the Gulf Country of Queensland at about 30 km/year during the early 1980s, and entered the Northern Territory in 1985. The front of their distribution is currently near the Roper River. Since 1986 a series of studies has been undertaken with several aims: to compare rates of reproduction, growth, and survival of toads between old and recently colonised populations and determine how these respond to the environment; to examine how toads affect native aquatic animals; and to examine patterns of movement by toads and how these respond to environmental conditions. We found no consistent differences between old and recently colonised populations. Female toads lay approximately 15 000 eggs each time they breed, can breed in any season, and may breed several times each year. Survival of eggs through the larval stage to metamorphosis is highly variable, depending strongly on which aquatic predators are present. Survival rates of terrestrial juvenile stages are also highly variable, depending on both predation rates and the availability of water to prevent desiccation. Growth and survival of toads above 30 mm in length depends strongly on water availability. All stages of the life cycle are toxic and are avoided by many native predators, but are successfully consumed by many others. The aquatic predators most negatively affected by toads appear to be native frog larvae and snails. Toad larvae can also compete strongly with larval native frogs. Adult toads do not have fixed home ranges, but move and select shelter sites in patterns strongly affected by water availability.*

Keywords: cane toads, *Bufo marinus*, population dynamics, effects on native fauna, movement, behaviour, invasions, shelter-site use

1 Introduction

This study was initiated as part of a program examining the possibilities for biological control of the cane toad, *Bufo marinus*, in northern Australia. *Bufo* were introduced at several locations on the east coast of Queensland in the 1930s. By the 1950s they had spread through much of the eastern seaboard of the state. They continued to spread westward, and in 1986 reached Calvert Hills Station in the Northern Territory. Their average rate of spread during the 1980s was 30 km/y. Studies by Covacevich and Archer (1975) and by Freeland and his associates (Freeland 1985, 1986; Freeland and Martin 1985; Freeland et al 1986a, 1986b) suggested that cane toads might pose a serious threat to many native species, that their range was expanding rapidly and would eventually include most of the wetter regions of the Northern Territory, and that older established populations might be declining. Freeland suggested that if older populations were declining it might be possible to use the agents responsible for those declines to slow or halt the northward and westward expansion of the range of *Bufo*.

The research program reported on in this paper was conducted in two phases. The goals of the first phase were to document and compare the density, dynamics, and factors controlling the numbers of aquatic and terrestrial stages of *B. marinus* in older and newly established populations. The second phase was carried out to answer several questions that arose from the results of the first phase: (1) What are the local and long-distance movements of *B. marinus*? (2) Do the eggs and larvae of *B. marinus* adversely affect freshwater communities in which they occur? (3) How do growth and survival of postmetamorphic *Bufo* respond to changes in the availability of food and moisture?

The first phase of the program was carried out primarily as two PhD projects by MN Hearnden (aquatic stages and reproduction) and MP Cohen (terrestrial post-metamorphs, juveniles, and adults). It examined populations of toads at Calvert Hills Station, Northern Territory (17°45'S, 137°19'E, first colonised 1986) and near Townsville, Queensland (19°21'S, 145°36'E, colonised in the 1950s). The second phase was carried out by MR Crossland (PhD project, effects on freshwater communities), D James (honours project, further detail on growth and survival of postmetamorphic animals) and L Schwarzkopf and RA Alford (local and long distance movements and shelter use). This phase examined populations near Townsville, Queensland and Heathlands Ranger Base, Cape York Peninsula (11°35'S, 142°33'E, colonised 1991). Each project used a combination of field observations and laboratory and field experiments.

For the purposes of the program, we divided the cane toad life history into six stages: eggs, hatchlings (emerged from eggs but not yet capable of coordinated swimming), tadpoles, metamorphs (from time of forelimb emergence to attainment of 30 mm snout-ischium length), juveniles (from 30 mm SIL to 90 mm SIL), and adults (SIL $\geq$ 90 mm). Ninety millimetres was chosen as the minimum size of adults because the sex of animals below this length cannot be reliably determined. Some individuals may be sexually mature at sizes as low as 65 mm SIL, but because fecundity increases rapidly with size, their contribution to the total reproductive output of populations would be minimal.

2 Methods, results and discussion

2.1 Reproductive seasonality, calling, and spawning

We examined the gonads of male and female toads collected from Townsville and Calvert Hills sites throughout the year. At all times during the year, the majority of males collected were capable of spawning, and some females were carrying mature ova. The proportion of females with mature ova peaked in the late dry season. Field observations showed that calling and spawning activity can occur in any month of the year, but peak in the wet season. Wet season reproductive activity levels were not closely correlated with rainfall or temperature, but were episodic, with a mean of 2.25 $\pm$ 0.7 (95% CI) egg masses deposited per 250 m of shoreline at intervals of 6.6 $\pm$ 3.5 days.

Female fecundity is related to female body size, increasing from 7500 eggs at 90 mm SIL to 20 000 at 140 mm. It is thus possible to predict egg input to populations using data on the size-frequency distribution of females and female population size. This will allow us to develop detailed models of toad population dynamics that incorporate age and size structure.

2.2 Abundance, growth, development, and survival of eggs, hatchlings, and larvae

In the field, eggs required 70 to 91 hours to develop between oviposition and the swimming tadpole stage. Mean survival to swimming tadpoles in field enclosures was 88% when predators were excluded, and < 1% when they were not. The most frequent predators of eggs and hatchlings observed in the field were older *Bufo* tadpoles. The aquatic stages of the cane toad were also vulnerable to a variety of native predators: crustaceans (*Cherax quadricarinatus, Holthusiana* sp., *Macrobrachium* sp.), larval dragonflies (*Hemianax papuensis, Pantala flavescens, Trapezostigma* sp.), adult and larval water beetles (*Cybister godefroyi, C.* sp., *Hydaticus vittatus, H.* sp., *Laccotrephes* sp., *Ranatra* sp.), notonectids (*Anisops* sp.), leeches (*Goddardobdella elegans*), and tortoises (*Emydura krefftii* and *Elseya latisternum*) preyed on eggs, hatchlings, or tadpoles in the field or in laboratory experiments.

Tadpole densities were estimated using box sampling (Hearnden 1991, Shaffer et al 1994) at Townsville and Calvert Hills sites in each season. Overall mean density when tadpoles were present varied from 15/m^2 to 61/m^2 (approximately 0.11/L to 0.45/L). Analysis of tadpole cohort size-frequency distributions indicated that the mean time for development from the end of the hatchling stage to metamorphosis was about 38 days in the field. The minimum larval period observed in experimental ponds at very low tadpole densities and similar temperatures was 16 days. These results suggest that *Bufo* tadpoles experience competition in the field. Results from experimental ponds also showed that reduced densities caused by predation on *Bufo* larvae allow the survivors of predation to metamorphose more rapidly and at larger sizes. They thus experience much higher rates of survival through the vulnerable metamorph stage (see below). Experimental pond results also demonstrated that older *Bufo* larvae prey heavily on the eggs and hatchlings of later cohorts. Taken together, these results indicate that any measures taken to reduce the rates of survival of aquatic stages, or the rate of reproduction of adults, are unlikely to have much effect on populations; instead, they are simply likely to increase the rates of growth and survival of the remaining tadpoles.

Approximate cumulative survival from egg to metamorphosis was: 10% under low-density predator-free conditions, 4% at normal field densities, 1% at field densities with odonate predators, 0.1% at field densities with older *Bufo* cohorts present, and 0.025% at field densities with older cohorts and odonates present. Survival varied widely, depending on tadpole density and the species and numbers of predators present.

2.3 Effects of eggs, hatchlings, and larvae on aquatic predators

We used laboratory and field experiments in containers and pens to evaluate whether toxic effects of aquatic stages of cane toads are likely to have adverse effects on populations of native freshwater predators. We found a surprisingly large number of predators that are capable of consuming some or all aquatic stages of toads with no apparent ill effects. These were listed in Section 2.2. Several other unexpected results emerged from this study. No native fish species were adversely affected by aquatic stages of *B. marinus*. We tested five fish species (*Ambassis agrammus, Craterocephalus stercusmuscarum, Hypseleotris compressa, Melanotaenia splendida, Neosilurus hyrtlii*). Most fish either ignored *Bufo*, or tasted and rejected them with no apparent ill effects. One *A. agrammus* and one *N. hyrtylii* each killed a single *Bufo* tadpole, and may have eaten it. The tadpoles of several species of native frogs, however, were vulnerable to cane toad toxins. Larval *Cyclorana novaehollandiae, Limnodynastes ornatus, Litoria bicolor, L. infrafrenata, L. nigrofrenata,* and *L. rubella* experienced high rates of mortality when exposed to cane toad eggs or hatchlings, although alternative food was available. Finally, freshwater snails (*Austropeplea lessoni*) experienced 100% mortality when toad eggs were present. These results suggest that while a wide variety of native predators can consume aquatic stages of toads without harm or can avoid consuming them, some species are very vulnerable, including the larvae of many native frogs and at least some species of snails.

2.4 Abundance, growth, development, and survival of metamorphs

Some of the results discussed here have previously been published (Cohen & Alford 1993). Abundance of metamorphs was determined by sampling within 1 × 1 metre quadrats at three distances from water, during the wet and early dry seasons at Townsville and Calvert Hills sites. At most sites, metamorphs spend from a few days to a few weeks near water. Dispersal rates increase with increasing soil moisture. Their movement away from water can be modelled as a biased diffusion process, leading to movement away from water at mean rates of ca 5 cm/d in the wet season and 2 cm/d in the dry. Overall mean densities 0-1 m from water were 2.6/m^2 in the wet season, 2.1/m^2 in the dry.

Growth and survival were measured in enclosures near water bodies. Initial experiments (Cohen & Alford 1993) showed that density affected rates of growth of metamorphs but not daily survival rates; the combination of these results indicates that density can alter cumulative survival from metamorphosis to juvenile size (30 mm SIL). Cohen and Alford (1993) showed that a fivefold increase in density (from 3.3 to 16.7/m^2) would lead to decreases of 50–80% in the proportion of individuals surviving from metamorphosis to 30 mm SIL. At field densities (3.3/m^2), Cohen and Alford estimated that growth from metamorphosis to 30 mm would require 50, 101, or 81 days with 3.1, 1.2, or 17.6% survival (Calvert Hills wet and dry seasons and Townsville dry season, respectively). Later experiments (James 1994) showed that growth rates are affected by the type and density of vegetation near water (generally increasing with increasing density of low vegetation cover), soil moisture (higher moisture leads to higher growth rates), and density. All of these factors interact with the availability of retreat sites such as cattle hoofprints; as conditions become more stressful, retreat sites become more important and are used more frequently.

The high degree of density dependence observed in these experiments suggests that for the metamorph stage, as for the aquatic stages, management practices or control measures that serve only to reduce density are not likely to strongly affect populations. Reducing the numbers of metamorphs in an area simply releases remaining individuals from the negative effects of density. The data do suggest, however, that reducing the availability of retreat sites and soil moisture might decrease growth and survival rates of metamorphs.

2.5 Juvenile and adult population sizes and survival rates

Mark-recapture censuses were conducted at least four times each year, from late 1986 through 1992, at six primary sites: three at Calvert Hills and three near Townsville. These followed a two-stage sampling design: each census included three sampling nights in near succession. Each sample was conducted for one hour, in either a 10 *x* 100 metre transect parallel to a large body of water or in a 10 m wide belt completely around a smaller water body. Each animal captured was sexed, weighed, measured, marked using individual toe-clips, and released. During field work on movements in 1992 and 1993 (see below), toes removed were retained, decalcified, sectioned, and used to estimate standing age distributions of adult toads by counting growth rings.

The marking technique did not affect probability of recapture; there was no relationship between proportion of animals recaptured and number of toes removed. Recaptures on the second and third nights of each census were used to calculate Petersen estimates (Begon 1979) of the size of male, female, and juvenile populations. The data for each census were also lumped, and the Jolly technique (Begon 1979) was used to estimate combined rates of death plus emigration between censuses.

Mean values for the Petersen estimates taken at each Calvert Hills and Townsville site in each season from 1987–1992 appear in figure 1. These show that populations fluctuate considerably between seasons and years. There are no obvious differences between 'old' (Townsville) and 'new' (Calvert Hills) populations. Male populations are more predictable than female ones; this probably reflects the fact that a higher proportion of males than females is active in the terrestrial catchment area of each water body on most nights. Juvenile recruitment was highly variable between years, but appears to have been correlated among sites within regions. This variation was probably largely caused by variations in the amount and temporal pattern of rainfall that modified rates of growth and survival of metamorphs.

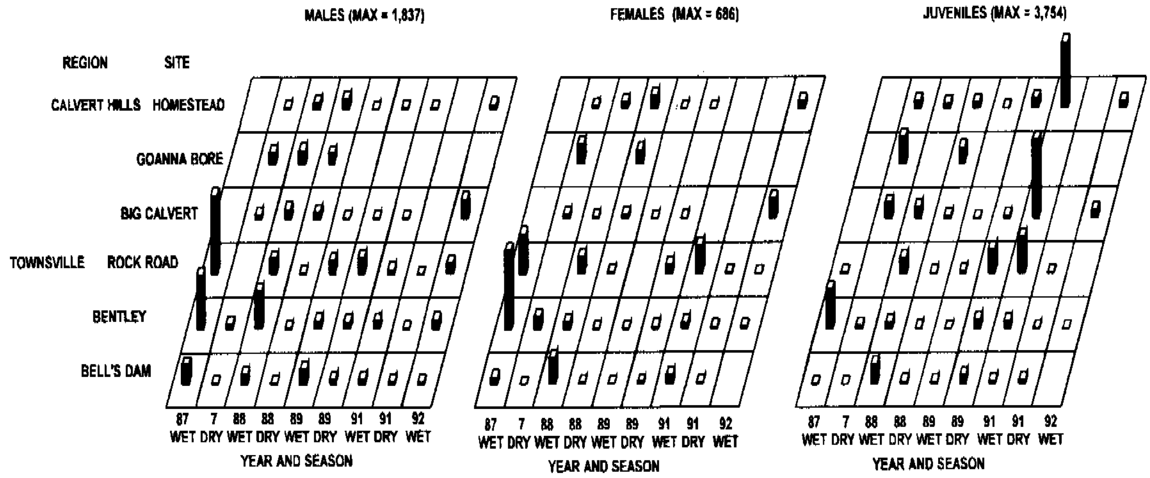

Figure 1 Mean Petersen estimates of sizes of male, female, and juvenile toad populations at three 'old' (Townsville) and three 'new' (Calvert Hills) sites during 1987–1992

Rates of death plus emigration were very high: mean rates were approximately 1%/d for adults, higher for juveniles. Most recaptures occurred within 90 days of first capture, very few (from 1 to 10%) occurred > 365 days after the date of first capture. The skeletochronological work carried out in 1992 and 1993 suggested that adult toads in the Heathlands area survive at rates of approximately 30–70% per year. Combined with these results, the mark-recapture results indicate high rates of emigration from the sampled sites.

2.6 Juvenile and adult activity patterns

In order to evaluate whether one-time counts might accurately reflect the size of cane toad populations, we examined the proportion of each population that was active near water during each night of each census. This varied from 5% to 80%. It was not related to night (1,2,3) of census, indicating that censusing activity did not affect toad activity levels. It varied between seasons and regions and was affected by total rainfall in the month before the sample; the proportion of adults active near water decreased with increasing rainfall in the dry season, suggesting that the primary purpose of activity near water in that season is rehydration. During the wet season, the proportion of males active near water increases with increasing rainfall, probably reflecting levels of male interest in breeding. Neither rainfall nor any other environmental variable accounts for enough of the observed variation in proportion active to allow correction of one-time censuses to accurately reflect the size of toad populations.

2.7 Juvenile and adult body condition

We used mass $^{1/3}$/SIL as an index of toad body condition. Condition was affected by seasonal rainfall, and was usually similar for males, females, and juveniles within regions and seasons. The average body condition of Townsville toads was slightly lower than that of Calvert Hills toads; this may reflect a combination of greater water stress in Townsville populations and the effects of higher toad densities in the Townsville region on local abundances of food items near water.

2.8 Juvenile and adult growth rates

We estimated growth rates of juvenile and adult toads using data from medium-term recaptures (> 30 days, < 150 days). Growth rates of males and females were similar, but growth differed between regions. We thus combined the data on both sexes for each region to increase the accuracy of estimates. The best-fit curves are presented in figure 2. These indicate that toads grew more rapidly at Calvert Hills than in the Townsville region, but that Townsville toads attained greater asymptotic sizes. We used the 95% confidence limits for the mean of each growth curve to estimate the minimum, mean, and maximum values for mean time from 30 mm to 90 mm SIL in each region. These also appear in figure 2. Combined with the estimates of growth rates of larvae and metamorphs, they suggest that best estimates of mean time from egg to adult during the Phase I study are approximately 546 days for toads in the Townsville region and 338 days for Calvert Hills toads. This suggests that the 'new' populations had shorter generation times and thus greater potential rates of increase than the 'old' populations.

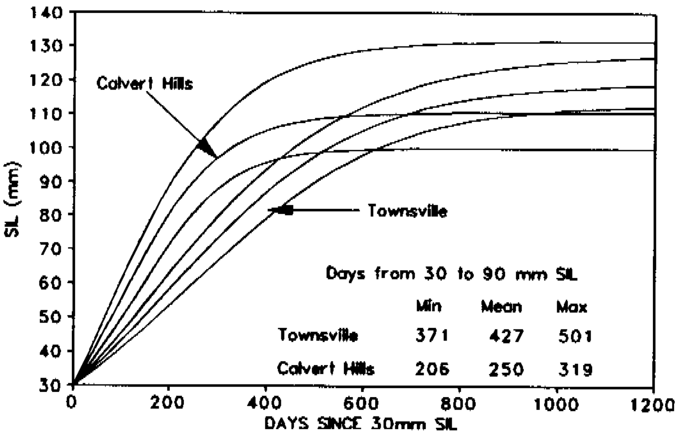

Figure 2 Gompertz growth curves for juveniles and adults, with 95% confidence limits

2.9 Patterns of movement by adults

We used radio-tracking to monitor movements of adult toads near Townsville ('old' populations) and at Heathlands Ranger Base ('new' populations) during the wet and dry seasons. We tracked 53 animals, for an average of 28 days each. Each animal was located during the day (usually in a shelter site), in the early night, and in the late night/early morning hours. Patterns of movement and shelter-site use differed between males and females and changed seasonally. Both sexes showed greater fidelity to shelter sites in the dry season than in the wet season. During the wet season, males tended to move between shelter sites and water bodies, while females moved greater distances and visited water bodies less frequently. Neither sex appeared to have fixed home ranges. Toads adopted restricted activity ranges for variable periods, but some animals moved excursively during each tracking period. The proportion of excursive movements increased in the wet season; toads often moved several hundred metres or more and did not return. The types and usage of shelter sites changed seasonally. In the dry season toads tended to use burrows or shelter sites relatively near water, to emerge less often, and to repeatedly return to the same shelter site. In the wet season, more open shelter sites farther from water were used and toads emerged more frequently and returned to the same shelter site less often.

Water evaporates from toads and from agar models at the same rate (Wygoda 1984). We used agar models placed in shelter sites to estimate rates of desiccation of toads during each season. The results of this agreed with the radio-tracking data. The need to visit water for rehydration is minimised by use of burrows during the dry season, while in the mid-wet season, water does not limit toad movements or retreat site selection. This allows toads to disperse widely during the wet season, following gradients of resource availability or searching for reproductive habitat.

We have used our data on toad movements to construct a preliminary simulation model of toad movement patterns. It incorporates our empirical distributions of probability of emergence from shelter sites, distances and angles moved, and probability of return to shelter sites. This model will be refined further, but already produces movement patterns and total displacements over 28 day intervals that are similar to observed data for most combinations of region and season. It predicts mean displacements of approximately 9 km/y for toads at Heathlands, and 6 km/y for toads in the Townsville region. Typical outputs appear in figure 3.

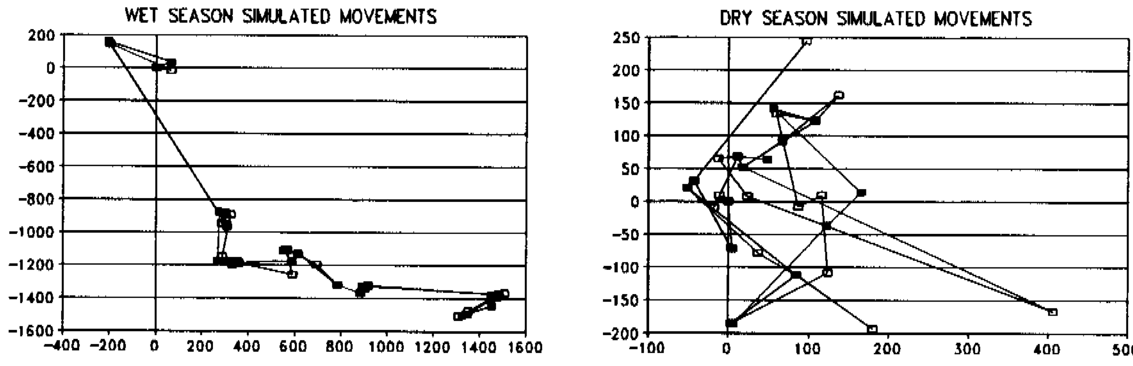

Figure 3 Simulations of movements over 30 days by adult toads during the wet and dry seasons. Open squares denote activity sites, closed squares are retreat sites. Note the differences in scale

2.10 Model of toad population dynamics

We have combined the estimates of reproductive rates, growth rates, and mortality at each life history stage to produce a preliminary stage-based compartment model of toad population dynamics. This model is incomplete, as it does not as yet incorporate information on density-dependence and ignores seasonal effects. Data on those influences are available and will be incorporated. This will produce a useful model for exploring the effects of various management and control strategies on *Bufo* populations. With some simple random variation in transition probabilities incorporated, our preliminary model mimics the behaviour of real toad populations in a reasonable manner. Figure 4 illustrates the outcome of a run with the transition probabilities between life history stages set to near modal values and allowed to vary randomly.

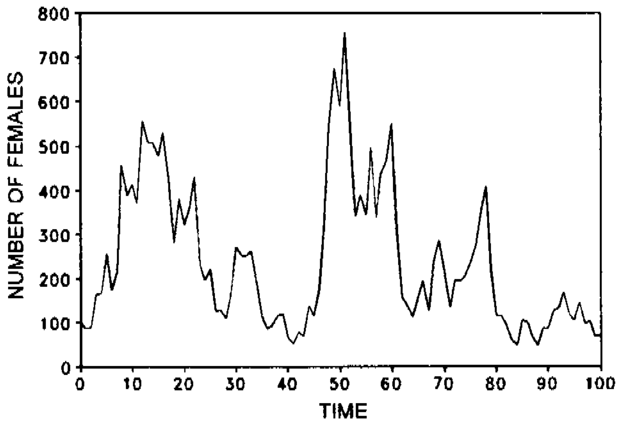

Figure 4 Dynamics of adult females in a simulated toad population

3 Summary and conclusions

Cane toads are vulnerable to a wide range of predators and other sources of mortality during their aquatic stages. They occur in aquatic habitats and nearby terrestrial habitats during the first stages of their lives at high densities that lead to substantial density-dependent mortality. Aquatic stages of toads may pose a threat to some components of native freshwater communities, particularly native frog larvae and snails. Management or control measures that are aimed at reducing densities of aquatic stages, either by reducing adult reproductive rates or killing eggs, hatchlings, or larvae, may reduce the effects of these stages on native species but are unlikely to have strong effects on the densities of juvenile and adult toads, as decreases in density of the early life-history stages will simply lead to better growth and survival rates of remaining individuals. Juvenile and adult toads are highly dispersive, apparently lacking fixed home ranges, but are highly vulnerable to desiccation. It is likely that desiccation caused by the selection of low-quality shelter sites during the dry season is a substantial source of mortality in juvenile and adult toads. It appears likely that the control measures that will be most effective at reducing toad numbers and minimising their impact will be ones that attack the terrestrial juvenile and adult stages.

Acknowledgments

This research was supported by grants and research contracts from the Council of Nature Conservation Ministers, the CSIRO, and James Cook University to RA Alford. A previous draft was improved by comments from LMJ Alford.

4 References

Begon M 1979. *Investigating Animal Abundance: Capture-Recapture for Biologists.* Edward Arnold, London, pp97.

Cohen MP & Alford RA 1993. Growth, survival, and activity patterns of recently metamorphosed *Bufo marinus. Wildlife Research* 20, 1–13.

Covacevich J & Archer M 1975. Distribution of the cane toad, *Bufo marinus* in Australia and its effects on indigenous vertebrates. *Memoirs of the Queensland Museum* 17, 305–310.

Freeland WJ 1985. The need to control cane toads. *Search* 16, 211–215.

Freeland WJ 1986. Populations of the cane toad, *Bufo-marinus*, in relation to time since colonization. *Australian Wildlife Research* 13, 321–330.

Freeland WJ, Delvinquier BLJ & Bonnin B 1986(a). Decline of cane toad, *Bufo marinus*, populations: status of urban toads. *Australian Wildlife Research* 13, 597–601.

Freeland WJ, Delvinquier BLJ & Bonnin B 1986(b). Food and parasitism of the cane toad, *Bufo marinus*, in relation to time since colonization. *Australian Wildlife Research* 13, 489–499.

Freeland WJ & Martin KC 1985. The rate of range expansion by *Bufo marinus* in northern Australia, 1980-1984. *Australian Wildlife Research* 12, 555–559.

Hearnden MN 1991. The Reproductive and Larval Ecology of *Bufo marinus* (Anura: Bufonidae). PhD. Thesis, James Cook University, Townsville, Australia, 245pp.

James D 1994. Ecological Determinants of Survival, Dispersal, and Growth in Newly Metamorphosed *Bufo marinus*. Honours thesis, James Cook University, Townsville, Australia, 112 pp.

Shaffer HB, Alford RA, Woodward BD, Richards SJ, Altig RG & Gascon C 1994. Quantitative sampling of amphibian larvae. In *Measuring and Monitoring Biological Diversity: Standard Methods for Amphibians*, (eds) WR Heyer, MA Donnelly, RW McDiarmid, LC Hayek & MS Foster. Smithsonian Institution Press, Washington. 130–142.

Wygoda ML 1984. Low cutaneous evaporative water loss in arboreal frogs. *Physiological Zoology* 57, 329–337.

DEVELOPING A WEED MANAGEMENT STRATEGY FOR A CONSERVATION AREA

MJ STORRS & WM LONSDALE[1]

ANCA, Kakadu National Park, PO Box 71, Jabiru, NT 0886,
[1]CSIRO Division of Entomology, PMB 44, Winnellie, NT 0821

ABSTRACT

Kakadu National Park ecosystems, especially wetland and riparian habitats, are under threat of invasion from a number of weed species. Invasive weed species affect both the structure and function of an ecosystem. Although management priority must be given to controlling particular invasive weed species in the short term, in the longer term a more holistic approach should be taken to weed management in general. The underlying philosophy must be one of regarding weeds as a symptom of land management practices and addressing those causes, rather than simply attempting to eradicate individual species.

This strategic approach involves the long-term planning of large-scale operations that integrate programs on fire management, feral animal control, management of visitor use, rehabilitation of degraded land and revegetation using native species. The Kakadu National Park Board of Management has requested that a Weed Management Strategy be developed from extensive consultation with Aboriginal traditional owners, the Park's field staff, regional research bodies and local and international weeds experts. This paper describes some of the general principles of weed management and the process involved in developing such a strategy.

Keywords: weeds, threats, introduced plants, naturalised alien plants, weed control, management strategy, conservation areas, national parks, Kakadu National Park.

1 Introduction

Invasion by introduced plants constitutes one of the most serious threats to the survival of natural ecosystems. This is not fully acknowledged by conservationists (Heywood 1989). Weed control in conservation areas is often accorded a low priority because it lacks glamour, it yields intangible results and it is perceived as a chronic resource drain. However, there is increasing recognition amongst conservation land managers that weed management must be a central goal. One of us (M Storrs) has been contracted to prepare a weed management strategy for the World Heritage listed Kakadu National Park. The aim of the strategy is to use the collective wisdom available locally and internationally to ensure that the weed control dollar is spent in the most effective way. We outline in this paper some of the general principles of weed management and the procedures involved in developing such a strategy.

We take the definition of a weed used by Cowie and Werner (1987) as *'any naturalised alien plant'*. A naturalised alien species is one that has become established and reproduced for several generations in the wild. The weediness of naturalised alien plants varies; some have little or no apparent impact, while a proportion (between 2 and 40%, Lodge 1993) are aggressive invaders that can successfully compete for niches previously occupied by native species. Such invaders modify the richness and abundance of other species and therefore alter the function of natural ecosystems (eg Braithwaite et al 1989, Lonsdale 1992).

About 15% of the overall Australian vascular flora are naturalised alien species (Humphries et al 1991). The Northern Territory, at 4 or 5%, has the lowest percentage of any State or Territory in Australia. This is a result, perhaps, of limited agricultural development and a small population (Humphries et al 1991), the seasonal aridity of monsoonal climatic regions (Usher 1988), and the low fertility of many northern Australian soils (Cowie & Werner 1993). Kakadu National Park has 89 naturalised alien species that represent 5.8% of its vascular flora (Cowie & Werner 1993). This is relatively low when compared with an average of 21% in other Australian conservation areas (Lonsdale 1992). More recent work suggests that the number of naturalised aliens in Kakadu may be as high as 102 but that they represent a smaller percentage (5.4%) of the total flora as the flora of the region becomes more fully described (K Brennan ***eriss***, unpub).

2 Strategic weed management

A weed *strategy* entails directing the large-scale, long-term operations of a weed control program (Moody & Mack 1988). Weed control *tactics* (ie the specifics of herbicide, and other control procedures) do not concern us here. Nevertheless, strategic weed management requires detailed planning and needs to be fully integrated in long-term management programs for the area. Area management rather than species management should be the focus. The underlying philosophy of any weeds management strategy should be to establish why weeds are present and address the causes, rather than killing weeds *per se*. This 'holistic' approach to weed management is the most appropriate for conservation areas, but it is seldom undertaken. Consideration must be given to: prevention; surveillance and intervention; identifying plant community types prone to invasion; decreasing an area's susceptibility to invasion; and managing existing weeds.

2.1 Prevention

One of the most powerful weapons against weed incursions is to prevent them in the first place. Around half of Australia's noxious weeds were introduced intentionally (Panetta 1993). Changes to Australian Quarantine Protocols are underway to introduce risk assessment of species not previously known as weeds.

On a more local level preventing weeds entering conservation areas can be achieved by education and enforcement. Liaison with adjacent landholders and Landcare groups in shared catchments is necessary, while control of plantings of aliens within a Park is absolutely vital. Soil, construction material and vehicles (such as road-building and maintenance equipment and grass-slashers) are likely to be major carriers of weed seeds and propagules into conservation areas. There is therefore a need to institute control procedures and provide vehicle washdown facilities. Tourist vehicles seem to have a very low density of seed; most carry no seeds, or only one seed (Lonsdale & Lane 1994).

2.2 Surveillance and early intervention

Another powerful weapon against the weed threat is early intervention. Major sites for potential invasion need to be determined. For example, weeds often establish in areas of high recreation use, and are dispersed by people, animals, wind, water and road-building equipment and grass-slashers. Routine monitoring of such high risk areas for 'new' weed species needs to be undertaken. Training of rangers in alien and native flora identification is therefore a priority.

2.3 Identifying plant community types prone to invasion

Certain types of plant communities are more prone to invasion by weeds than others, for example, riparian systems are usually the most heavily weed-infested areas in any region. In fact, all the critical (highly invasive) weed species identified by (Humphries et al 1991) are either restricted to floodplain habitats or form the densest infestations along watercourses. *Tropical wetlands, in particular, are in critical danger.* This is of profound ecological significance given the key nature of these habitats to the survival of many native animals (Braithwaite 1985, 1990) including migratory species for which the Australian Government has signed international conservation conventions.

2.4 Decreasing an area's susceptibility to invasion

A key strategy for weed management in conservation areas is the minimisation of ecological disturbance. Weeds generally appear in areas that have been subjected to some form of disturbance (Hobbs 1991, Hobbs & Huenneke 1992). Although all areas experience some level of disturbance, be it from seasonal flooding, fire or grazing by native animals, and are therefore susceptible, in varying degrees, to invasion by weeds some experience more profound disturbance, usually from human activity or from feral animals. The removal of feral animals, management of visitor use, rehabilitation and revegetation using native species, and the use of fire all need to be integrated into a weed management strategy.

2.5 Managing existing weeds

Many major weed infestations in conservation areas are a legacy of previous land uses. A prerequisite for a weed management program is a detailed survey of the area to determine what naturalised exotics are present, highlight critical invasive species and key parts of the landscape threatened, determine appropriate control methods and prioritise resources accordingly. Physical and chemical control methods can be appropriate especially when integrated with other methods such as biological control (eg Storrs & Julien, in press), manipulation of fire regimes and the promotion of growth of indigenous plants. Although it is necessary to continue to control particular highly invasive weed species in the short-term, the longer-term aim is to maintain alien plant populations at an acceptable level by managing the habitat and, if available, by biological control. In the past, perhaps too much emphasis has been placed on the removal of undesirable plants while neglecting to re-introduce or encourage native species.

3 Alien plants in Kakadu

In their survey of alien plants in Kakadu, Cowie and Werner (1993), found 374 alien species, many of which were under active cultivation around homes and businesses located within the Park, particularly in the township of Jabiru. Only 89 species were considered to be naturalised although other species may be a potential problem in the future.

Most of the naturalised alien species in Kakadu have a limited distribution mainly associated with human activity such as roadways, borrow pits, settlements, campgrounds and other disturbed areas. Kakadu will continue to be disturbed by human activity.

Tourism, mining and pastoralism are conducted adjacent to and within the Park boundaries. Tourism has undergone a remarkable expansion in the Park since its declaration. Tourist numbers for 1982 were estimated at 45 000 while in 1994 approximately 240 000 people visited the Park. Along with the increase in visitor numbers there has been an increase in the average number of days each visitor spends in the Park and this has been followed by an expansion in infrastructure and tourist facilities.

Jabiru, a township of around 1500 people, is situated within the Park as are a number of other settlements including Aboriginal living areas. Aboriginal people continue to use their lands within the Park for hunting and gathering.

A large proportion of the weed flora of Kakadu existed in the area prior to establishment of the Park reflecting the past land use of the area, particularly pastoralism. Introduced pasture grasses are perhaps the most insidious and uncontrolled threats to the native communities of northern Australia (Lonsdale 1994).

Of the 'natural' communities surveyed, the habitats adjacent to floodplains and creeks were found to be the most severely infested in the Park (Taylor & Dunlop 1985, Cowie & Werner 1993). The invasion of alien plants in these riparian communities was largely due to disturbance by feral animals, in particular the water buffalo (*Bubalus bubalis*) (Braithwaite et al 1984). Under the Commonwealth's Brucellosis and Tuberculosis Eradication Campaign (BTEC) buffalo numbers in the Park have recently been reduced to very low levels (less than 200). Following buffalo reduction (approximately 100 000 buffalo and cattle ex Kakadu between 1979 and 1994 - BTEC records) the recovery of vegetation and amelioration of land degradation has been dramatic. However, there are indications that since buffalo removal, damage by feral pigs (*Sus scrofa*) is becoming more widespread on floodplain edges and riparian zones which is a major cause for concern. Groups of pigs can root up several hectares of sedgeland in a night and remove all tree regeneration in woodlands adjacent to floodplains. Feral horses (*Equus caballus*) are also abundant on wetland areas in the region especially in upper catchments.

Kakadu's wetlands are currently under threat from mimosa (*Mimosa pigra)*, a highly invasive neotropical shrub, the aquatic fern salvinia *(Salvinia molesta*), and the African pasture species para grass *(Brachiaria mutica*). Para grass, which is currently being promoted for ponded pasture elsewhere in the Territory, is infilling tropical wetlands and threatening waterfowl habitat (Humphries et al 1991). Two highly invasive introduced pasture grass species, gamba grass *(Andropogon gayanus*) and mission grass *(Pennisetum polystachion*), are threatening the savanna. They are vigorous tall perennials which have the capacity to increase markedly the impact of fire in lowland woodland and forest communities. Apart from the problems of controlling existing weeds there is the seemingly inexorable advance of potential invaders such as rubber vine *(Cryptostegia grandiflora*) and siam weed (*Chromolaena odorata*). Rubber vine currently has invaded more than three million hectares of mostly riparian habitat in north Queensland (McFadyen & Harvey 1990).

4 Current weed control in Kakadu

The Kakadu National Park Board of Management have emphasised that there is a need for increased planning in weed management and requested that resources be more carefully prioritised. The present Kakadu National Park Plan of Management (ANPWS 1991) states that the long-term objective is to eradicate all weeds from the Park. In reality, there is no practical technology available to achieve eradications of large weed infestations and attempts using chemical methods could result in massive degradation of the environment.

Considerable resources are allocated each year for researching and controlling weeds in Kakadu (approximately $700 000 or 7% of the Park's operational budget in 1994–95) and major achievements have been made particularly in regard to the management of mimosa (Cook et al, in press) and salvinia (Storrs & Julien, in press). Major alien plant surveys have been conducted by Cowie and Werner (1987, 1988) and by Brock and Cowie (1992). Follow-up surveys are to be undertaken at approximately 5 yearly intervals.

5 Developing a strategy for Kakadu

The Board of Management has requested that a weed management strategy be developed from extensive consultation with Aboriginal traditional owners, Park staff, regional research bodies and local and international weeds experts. The aim is to develop a strategy for Kakadu that is integrated with the Northern Territory Weed Strategy and the National Weed Strategy. The development process will entail six steps, which are described below.

5.1 Research - identification of objectives

The first stage involves a literature review of weed management in conservation areas around Australia and overseas to determine the state of current knowledge. This work will expand and develop the work that has already been done in the Park (eg Cowie & Werner 1987). Consultation will take place with key players and other agencies responsible for the implementation of existing weed control programs to determine realistic objectives.

5.2 Preparation of discussion paper

Following the research phase, a discussion paper will be produced and circulated for comment. This will list the objectives, basic principles and guidelines and develop a conceptual weed management framework.

5.3 Consultative period

The consultation phase will include face-to-face interviews with a wide range of individuals involved and interested in improving weed management in Kakadu. These individuals will include Aboriginal traditional owners, representatives of Aboriginal associations, Kakadu Project and District staff, adjoining landholders and landcare groups, and professionals involved in weed control. Consideration will be given to the most appropriate management techniques and the order in which they should be implemented.

5.4 Draft strategy

Following the consultative process a draft strategy will be prepared and circulated for comment. It will include recommendations:

5.4.1 For the short-term on

- weed management objectives by habitat within each of the five management districts of Kakadu including main sites of weed infestation and prioritisation of weed species
- responsibilities within Park staff and allocation of resources
- procedures (including safety issues)
- relationships with surrounding landholders, other government agencies and Aboriginal associations

5.4.2 For the long-term on

- land management objectives such as the minimisation of disturbing influences and the rehabilitation and revegetation of disturbed sites
- prevention of introductions of new weeds
- instigation of monitoring procedures for early intervention in cases of new weed incursions
- research needs (see Appendix)
- performance indicators

5.5 Workshop

It is proposed to convene a workshop for all interested participants to review and refine the strategy, and develop milestones (which should be reviewed every 5 years).

5.6 Finalisation of strategy and implementation

Taking into account all of the above, the final strategy will be drafted. It would be most unlikely that the final strategy document would achieve universal support - the Park, its people, and its users, are too diverse for that. However, it is hoped that, by undertaking extensive consultation, it would embody the state of current knowledge and opinion and would therefore provide directions that most people could support most of the time.

Once the document is complete, the process of strategically managing weeds in Kakadu will have only just started. A great deal of effort will be needed to ensure that the strategy is implemented to the best effect possible, and that it continues to remain relevant and valid. Periodically the strategy will have to be reviewed to ensure that it is not straying too far from the best interests of the Park, or being left behind by the ever-changing tropical weed agenda.

6 Conclusion

We believe a strategy that regards weeds as a symptom of land management practices is likely to be more effective in the long run than a program which has no objective except weed eradication. Under our philosophy, the emphasis is on controlling the conditions that allow weeds to thrive, and on aiding the recovery of the native vegetation to increase its resistance to alien weed incursion. Weed control is then subsumed within the overall goals of conservation management.

Acknowledgments

We wish to thank G. Cook, P. Barrow, J. Russell-Smith, G. Fien, K. Duigan and H. Moorcroft for helpful comments on the manuscript.

7 References

ANPWS 1991. *Kakadu National Park Plan of Management.* Australian National Parks and Wildlife Service, Canberra.

Braithwaite RW (ed) 1985. *The Kakadu Fauna Survey: An Ecological Survey of Kakadu National Park (report to ANPWS, Canberra).* CSIRO, Division of Wildlife and Rangelands Research, Darwin.

Braithwaite RW 1990. Australia's unique biota: implications for ecological processes. In *Savanna Ecology and Management*, (ed) PA Werner, Blackwell Scientific Publications, Oxford, 3–10.

Braithwaite RW, Dudzinski ML, Ridpath MG & Parker BS 1984. The impact of water buffalo on the monsoon forest ecosystem in Kakadu National Park. *Australian Journal of Ecology* 9, 309–322.

Braithwaite RW, Lonsdale WM & Estbergs JA 1989. Alien vegetation and native biota in tropical Australia: the impact of *Mimosa pigra*. *Biological Conservation* 48, 189–210.

Brock J & Cowie ID 1992. Kakadu National Park: Review of Approved Plants List and Survey of Alien Plants at Settlements within the Park. Unpublished report to ANPWS, Canberra, Conservation Commission of the Northern Territory, Darwin.

Cook GD, Setterfield SA & Maddison J (in press). Shrub Invasion of a Tropical Wetland: Implications for Weed Management. *Ecological Applications*.

Cowie ID & Werner PA 1987. Weeds in Kakadu National Park - A Survey of Alien Plants. Unpublished report to ANPWS, Canberra, CSIRO Division of Wildlife and Rangelands Research, Darwin.

Cowie ID & Werner PA 1988. Weeds in Kakadu National Park - A Survey of Alien Plants. Phase II. Unpublished report to ANPWS, Canberra, CSIRO Division of Wildlife and Ecology, Darwin.

Cowie ID & Werner PA 1993. Alien plant species invasive in Kakadu National Park, tropical northern Australia. *Biological Conservation* 63, 127–135.

Heywood VH 1989. Patterns, extents and modes of invasions by terrestrial plants. In *Biological invasions: a global perspective*, (eds) JA Drake, HA Mooney, F di Castri, RH Groves, FJ Kruger, M Rejmanek & M Williamson, Wiley and Sons, Chichester, 31–60.

Hobbs RJ 1991. Disturbance a precursor to weed invasion in native vegetation. *Plant Protection Quarterly* 6, 99–104.

Hobbs RJ & Huenneke LF 1992. Disturbance, diversity, and invasion - implications for conservation. *Conservation Biology* 6, 324–337.

Humphries SE, Groves RH & Mitchell DS 1991. Plant invasions of Australian ecosystems - a status review and management directions. *Kowari* 2, 1–134.

Lodge DM 1993. Biological invasions: lessons for ecology. *Trends in Ecology and Evolution* 8, 133–137.

Lonsdale WM 1992. The impact of weeds in national parks. In *Proceedings of the International Weed Control Congress*, Vol. 1, (eds) JH Combellack, KJ Levick, J Parsons & RG Richardson, Weed Science Society of Victoria, Melbourne, 145–149.

Lonsdale WM 1994. Inviting trouble: introduced pasture species in northern Australia. *Australian Journal of Ecology* 19, 345–354.

Lonsdale WM & Lane AM 1994. Tourist vehicles as vectors of weed seeds in Kakadu National Park, Northern Australia. *Biological Conservation* 69, 277–283.

McFadyen RE & Harvey GJ 1990. Distribution and control of rubber vine, *Cryptostegia grandiflora*, a major weed in northern Queensland. *Plant Protection Quarterly* 5, 152–155.

Moody ME & Mack RN 1988. Controlling the spread of plant invasions: the importance of *nascent foci*. *Journal of Applied Ecology* 25, 1009–1021.

Panetta FD 1993. A system of assessing proposed plant introductions for weed potential. *Plant Protection Quarterly* 8, 10–14.

Storrs MJ & Julien MH (in press). A Handbook for the Integrated Control of *Salvinia molesta* in Kakadu National Park, ANCA, Canberra.

Taylor JA & Dunlop CR 1985. Plant communities of the wet-dry tropics of Australia: the Alligator Rivers Region, Northern Territory. In *Proceedings of the Ecological Society of Australia: 13. Ecology of the Wet-Dry Tropics*, (eds) MG Ridpath & LK Corbett, Blackwell Scientific Publications, Melbourne, 83–127.

Usher MB 1988. Biological invasions of nature reserves: a search for generalisations. *Biological Conservation* 44, 119–135.

8 Appendix

Research Needs

As the purpose of this workshop is to identify research priorities, we attach a list of under-researched areas in the field of environmental weeds.

- Identify the impact of weeds on natural ecosystems. It is not enough to continue to produce lists of 'major environmental weeds', without demonstrating what effects, if any, they have at an ecosystem level. In the wetlands of the Kakadu region research to quantify the effects of the aquatic fern, salvinia, and the pasture grass, para grass, are a priority.
- Investigate and document the susceptibility of specified ecosystems to weed invasion, particularly in reference to potential weed threats.
- Determine the major disturbing agents and ways of minimising this disturbance. In particular visitor use, feral animal control and fire management all need to be addressed. For instance, in Kakadu, little is known of the numbers, distribution behaviour and effects of feral pigs.
- Conduct controlled experiments on different types of disturbance and how they change an ecosystem's susceptibility to invasion. It would also be useful to ascertain under what conditions particular problem species become a dominant element of the flora.
- Develop strategies for the rehabilitation and restoration of disturbed areas; this will entail gathering more knowledge of the biology of the indigenous species that may compete successfully with the introduced weeds in a revegetation program. Rehabilitation of riparian systems in Kakadu is a priority.
- Determine ways in which established agricultural and forestry practices, particularly the use of chemicals and fire, can be adapted for controlling weeds in natural and semi-natural areas. Control methods for para grass are a priority in Kakadu.
- Determine the effects of control techniques on the environment. The long-term effects of some commonly used herbicides are not known, and their effects on non-target species must continue to be monitored.
- Establish long-term research projects to investigate the ecology of the most aggressive weed species (both existing and potential), and where possible biological control.

WEED THREATS TO NORTHERN TERRITORY WETLANDS

IL MILLER & CG WILSON

Department of Primary Industry and Fisheries,
PO Box 79, Berrimah, NT 0828

ABSTRACT

The well known exotic weeds Mimosa pigra *and* Salvinia molesta *are just two of the many species that pose a threat to the Northern Territory's wetlands. Other potentially serious weeds occur in the NT, which have either been controlled, or are still in a lag phase of weed development. For example, water hyacinth has occurred in the NT for at least 21 years, while* Barleria *spp. have only recently been identified as weeds of wet areas.*

Para grass, olive hymenachne, and aleman grass, are valuable pasture species and will assist in control of wetland weeds. However they are considered to be weeds of wetlands in conservation reserves and National Parks, hence there is a conflict over their use.

Weeds which do not occur in the NT, but which pose a threat are alligator weed, rubber vine, and creeping sensitive plant, plus a number of aquatic weeds. Their adverse impacts can be minimised by public education and appropriate management.

Keywords: wetland weeds, weed management

1 Introduction

The definition of wetlands can be very broad. For example, Paijmans et al (1985) defined wetlands as land permanently or temporarily under water or waterlogged, although they stated that temporary wetlands must have surface water or waterlogging of sufficient frequency and/or duration to affect the biota. Hence, in the NT, wetlands can include areas that may be dry for substantial periods such as the black soil plains in the north and dry lakes in the arid areas.

Wetland weeds have been present in the Northern Territory since last century. Many, however, were not identified as being weeds for some time. For example mimosa (*Mimosa pigra*) was introduced to the NT in the 20 years prior to 1891 (Miller & Lonsdale 1987), but for 80 years it was confined to the Darwin City area, being first noticed near the Adelaide River township in 1952. In terms of weed spread, it can be classed as a 'sleeper' because it did not show its true potential as a weed until it reached its favoured habitat - the seasonally inundated black soil plains approximately 100 years after its introduction.

A lag phase, where a new weed is confined to a restricted area for a long period before becoming more widespread, is not uncommon (Baker 1965). However, other wetland weeds found in the NT are more rapid in their spread. Salvinia (*Salvinia molesta*) was introduced to the NT through the aquarium trade, first being identified in a pool at a Darwin plant nursery in 1976 (Miller & Wilson 1989). Within seven years of the first report in Darwin, 10 field infestations had been recorded including one in Kakadu National Park.

Other examples of both 'sleeper' weeds and those that spread rapidly, occur in the NT. In this paper we concentrate on the tropical wetlands and give examples of weeds that pose a threat to primary industry and conservation values, together with aspects of their management.

2 Weed threats

The plants which pose the greatest threats to Northern Territory's wetlands are listed in table 1. The detrimental effects of these wetland weeds have not been given as these have been documented elsewhere, for example by Humphries et al (1991).

2.1 Species present in the Northern Territory

The best known examples are mimosa and salvinia. Mimosa occurs from near the Fitzmaurice River in the west to Arafura swamp in central Arnhem Land. Salvinia occurs in the region from Mission Hole on Elizabeth Downs Station near the Daly River, to Nhulunbuy in eastern Arnhem Land. Salvinia has been eradicated from six sites. Within these broad areas many wetlands are not infested, hence both mimosa and salvinia still pose a threat.

Water hyacinth (*Eichhornia crassipes*) is known to have been in the Territory for 21 years, but there is now very little present due to effective eradication.

Parkinsonia (*Parkinsonia aculeata*) is basically a riparian species, but will grow on floodplains. It was introduced to Australia around the turn of the century as a shade tree for planting around bores, dams and homesteads. It is an adaptable legume, occurring from the South Australian border right through to the wetlands of the north. It does not appear to be as aggressive as mimosa in the wetlands and probably would not be as well adapted to prolonged, deep flooding, but it is a weed that needs to be watched.

Noogoora burr (*Xanthium occidentale*) also occurs from Central Australia right through to the northern wetlands. It is basically riparian but there is evidence from the Daly River and near the Adelaide River that it will grow on seasonally inundated floodplains.

The above plants are all regarded by both primary producers and conservationists as weeds. Other plants have dual status. Para grass (*Brachiaria mutica*), olive hymenachne (*Hymenachne amplexicaulis*), and aleman grass (*Echinochloa polystachia*), are valuable pasture species. They may also assist in the integrated control of wetland weeds such as mimosa (Miller 1992) but they are also considered to be weeds of natural ecosystems (Humphries et al 1991).

Para grass was established in the Darwin Botanic Gardens last century (Wesley-Smith 1973), but is now being called a weed in Australia as ecological awareness grows. It is not a 'sleeper' because it has been planted deliberately on pastoral leases. For example it was planted at Oenpelli in 1922 (Letts 1960) and on Mudginberri Station long before Kakadu National Park was declared. Calls are being made for prevention of its further propagation if costs outweigh its benefits as a pasture (Humphries et al 1991).

Pasture improvement is a legitimate form of land use, as is the maintenance of ecological values in natural ecosystems. Hence a conflict has arisen over the use of these species as pastures. Such a dilemma is not confined to the Northern Territory, and indeed it arises wherever there are multiple land uses.

Table 1 Weed threats to Northern Territory wetlands

Species	Common Name	Comments
Species already present in the NT		
Annona glabra	Pond apple	perennial tree
Barleria lupulina	Barleria	perennial shrub
Barleria prionitis	Barleria	perennial shrub
Brachiaria mutica	Para grass	perennial grass
Eichhornia crassipes	Water hyacinth	free floating aquatic
Echinochloa polystachia	Aleman grass	perennial grass
Hymenachne amplexicaulis	Olive hymenachne	perennial grass
Mimosa pigra	Mimosa	perennial shrub
Parkinsonia aculeata	Parkinsonia	perennial shrub
Salvinia molesta	Salvinia	free floating aquatic
Xanthium occidentale	Noogoora burr	annual herb
Potential weeds not yet in the NT but present elsewhere in Australia		
Alternanthera philoxeroides	Alligator weed	anchored floating aquatic
Cryptostegia grandiflora	Rubber vine	perennial shrub/scrambler
Egeria densa	Dense water weed	submerged aquatic
Elodea canadensis	Canadian pond weed	submerged aquatic
Lagarosiphon major	Lagarosiphon	submerged aquatic
Mimosa invisa	Creeping sensitive plant	perennial scrambling vine
Potential weeds - not yet in Australia*		
Coix aquatica	Job's tears	perennial grass
Echinochloa glabrescens	Barnyard grass	annual grass
Echinochloa stagnina		perennial grass
Equisetum ramossissimum ssp. debile		perennial grass
Eriochloa polystachya		perennial grass
Leptochloa chinensis	Sprangletop	annual/sometimes perennial grass
Leptochloa panicea	Sprangletop	annual/sometimes perennial grass
Limnocharis flava	Yellow sawah lettuce	emergent aquatic
Myriophyllum spicatum		perennial submerged aquatic
Rotala indica		terrestrial/aquatic annual herb
Rotala ramosior		terrestrial/aquatic annual herb
Sacciolepis interrupta		perennial grass
Salvinia cucullata		free floating aquatic
Salvinia natans		free floating aquatic
Trapa bicornis	Chinese water chestnut	free floating aquatic
Trapa maximowiczii	Chinese water chestnut	free floating aquatic

*Source: Michael (1989)

Aleman grass and olive hymenachne are limited in their distribution in the Northern Territory. On the one hand these grasses are being planted on pastoral leases, while on the other hand Humphries et al (1991) recommended that existing populations of olive hymenachne and aleman grass should be destroyed pending an evaluation of the benefits and costs of their importation for use as wet pastures.

New wetland weeds exist in the NT which so far have not had major impacts. Infestations of the ornamental barleria (*Barleria lupulina* and *B. prionitis*) have recently been found spreading aggressively along northern rivers and in swampy country. They have not been recorded as weeds elsewhere in the world, although they have caused concern in Queensland, and so their potential as invaders of wetlands is unknown. Their behaviour in a range of habitats suggests that they should be very carefully watched. *B. prionitis* was declared as a noxious weed in the Northern Territory in February this year and consideration is being given to declaring *B. lupulina*.

Pond apple (*Annona glabra*) is considered by Sainty and Jacobs (1994) to be a potential weed of tropical wetlands. It is known to be present in Darwin gardens.

2.2 Potential weeds: not yet in the Northern Territory, but occurring elsewhere in Australia

Of the wetland weeds that are established in Australia, but not yet recorded from the Northern Territory, alligator weed (*Alternanthera philoxeroides*) probably poses the greatest threat. It is a serious weed throughout the tropics and, although in Australia it is presently restricted to New South Wales, it clearly has the potential to become far more widespread.

Rubber vine (*Cryptostegia grandiflora*) occurs in creek and river systems from the north Queensland coast to near the NT border. It also grows away from the riparian environment on seasonally flooded plains. It is one of Australia's most serious weeds, being extremely aggressive, destroying the native vegetation and competing with pastures.

Creeping sensitive plant (*Mimosa invisa*) occurs in north Queensland and in Southeast Asia, being a weed of canefields, plantations and wet pasture areas. In parts of Thailand it grows together with *Mimosa pigra* and would be well suited to the Northern Territory.

The submerged aquatic plants, dense water weed (*Egeria densa*), Canadian pondweed (*Elodea canadensis*) and lagarosiphon (*Lagarosiphon major*) are mainly known from warm temperate regions of the world, but they could become established in northern water bodies.

2.3 Potential weeds: not yet in Australia

To discuss the potential weediness of plants not yet exposed to the northern Australian environment is a difficult task, and we can only realistically look at those recorded as weeds elsewhere in the tropics. Michael (1989) attempted to do this, listing 16 weeds of aquatic habitats and/or flooded rice fields. In his 'top nine' plants of greatest potential threat to northern Australia four are wetland weeds: the grasses sprangletop (*Leptochloa chinensis* and *L. panicea*) and barnyard grass (*Echinochloa glabrescens*), and the aquatic yellow sawah lettuce (*Limnocharis flava*).

Job's tears (*Coix aquatica*), a native of Southeast Asia, could also become a serious pest of our wetlands. It is a large stoloniferous grass and is a serious weed in Thailand's waterways.

3 Management of wetland weeds

As for most weeds, an integrated approach to management is best applied to wetland weeds. Initial prevention through establishment of quarantine areas and public education are paramount, but once a weed becomes established management can incorporate a combination of physical (manual or mechanical), chemical, biological and ecological methods. These methods have proven to be effective for management of wetland weeds in the Northern Territory. Three examples follow.

Water hyacinth has been effectively controlled in the Northern Territory through publicity about the threat of the plant, and asking the public to report new infestations. There is now very little, if any, water hyacinth in home aquariums and ponds. Water hyacinth has been eradicated from six of the seven known field sites by physical removal of plants. Eradication of the remaining infestation in Fogg Dam, the only site where herbicides have been used, has not yet been confirmed so it still remains a threat.

Salvinia has been eradicated from six of the fourteen known sites using a combination of physical (nets and hand removal) and chemical means. The early successes were a direct result of publicity, reports being made of salvinia in aquariums and in the field before infestations became too large to manage. Biological control with the weevil *Cyrtobagous salviniae* is proving to be successful but is cyclical in nature.

Mimosa is being effectively controlled at selected sites using an integration of herbicides, mechanical control (chaining), burning and revegetation either through regenerating native species or by sown pastures. In other areas biological control agents are being tested.

For prevention of establishment of those weeds which do not occur in the Northern Territory, for example rubber vine and alligator weed, on-going publicity and quarantine are the most effective methods of management. Early reports of infestations, followed by swift action using physical and chemical means and long-term monitoring of sites is the only way that eradication can be achieved if infestations are found. Plans are afoot to prevent the westward movement of rubber vine by establishing a National Rubber Vine Buffer Zone between Queensland and the Northern Territory under the National Weed Strategy which is still under consideration.

4 Priority research needs

There is an urgent need for research into the costs and benefits of the wetland pasture species para grass, aleman grass and olive hymenachne and their impact on native plant species diversity and wildlife. The potential for conflict needs to be averted.

Research into the biological control of Noogoora burr needs to be enhanced. Studies into the biology and control of barleria need to be initiated.

5 References

Baker HG 1965. Characteristics and modes of origins of weeds. In *The genetics of colonizing species*, (eds) HG Baker and GL Stebbins, Academic Press, New York, 147–172.

Humphries SE, Groves RH & Mitchell DS 1991. *Plant invasions of Australian ecosystems - a status review and management directions*. Australian National Parks and Wildlife Service Endangered Species Program, Project No. 58.

Letts GA 1960. Cattle management and pasture improvement in the high rainfall belt of the NT - an historical review of the establishment and spread of para grass at Oenpelli mission. Unpublished Report Animal Industry Branch.

Michael PW 1989. Review paper on weeds of concern to northern Australia. Unpublished report.

Miller IL 1992. Competition between *Brachiaria humidicola* and *Mimosa pigra*. *Tropical Grasslands* 26, 111–114.

Miller IL & Lonsdale WM 1987. Early records of *Mimosa pigra* in the Northern Territory. *Plant Protection Quarterly* 2 (3), 140–142.

Miller IL & Wilson CG 1989. Management of salvinia in the Northern Territory. *Journal of Aquatic Plant Management* 27, 40–46.

Paijmans K, Galloway RW, Faith DP, Fleming PM, Haantjens HA, Heyligers PC, et al 1985. *Aspects of Australian wetlands*. Technical Paper No. 44, CSIRO Division of Water and Land Resources.

Sainty GR & Jacobs SWL 1994. *Water plants in Australia*. 3rd edn, CSIRO Division of Water Resources.

Wesley-Smith RN 1973. Para grass in the Northern Territory - Parentage and propagation. *Tropical Grasslands* 7, 249–250.

THE CONTROL OF *MIMOSA PIGRA* ON THE OENPELLI FLOODPLAINS

GC SCHULTZ & PH BARROW

Department of Primary Industry and Fisheries,
PO Box 990, Darwin, NT 0801

ABSTRACT

The noxious weed Mimosa pigra *threatens the traditional lifestyle and economic development of the Gunbalanya community and the Magela floodplain in Kakadu National Park. A five year action plan commenced in 1991 to control the infestation in Arnhem Land using an integration of chemical, mechanical and ecological methods. In year four of the program the major infestation has been removed but seedling reinfestation continues to occur.*

Keywords: noxious weeds, *Mimosa pigra,* integrated control, herbicides, Aboriginal communities

1 Introduction

Mimosa (*Mimosa pigra*) probably entered the Northern Territory through the Darwin Botanic Gardens prior to the 1890s (Miller & Lonsdale 1987). From this introduction this noxious weed has spread to most floodplains from the Arafura to near the Fitzmaurice River. The largest infestation in Arnhem Land occurs on the floodplains north of the community of Oenpelli (Gunbalanya). This infestation started before 1983 when it came to the attention of weeds officers of the Northern Territory Government. Limited resources were available for its control.

Seed feeding biological control agents were released and a Commonwealth Employment Program developed in association with the Kunwinjku Association in 1987. This program included the employment of 12 workers from the community to control isolated plants on the plain and dense areas were aerially sprayed with dicamba (Miller & Schultz 1988). Other programs involving the Northern Land Council (NLC), the Department of Primary Industry and Fisheries (DPIF), the former Department of Aboriginal Affairs and the Australian National Parks and Wildlife Service (ANPWS) took place on part of the infestation between 1988 and 1990. These short term projects increased the local and political awareness of the problem and slowed the expansion of the infestation. In spite of this, the infestation at Oenpelli increased to over 8000 ha of dense to scattered mimosa by 1990. Isolated plants of mimosa have been found along the banks of the East Alligator River which forms part of the boundary of Arnhem Land and Kakadu National Park.

Since 1990 mimosa has been found in other areas of Arnhem Land. These are Mekinj valley, Mt Borradaile, Murgenella, Tomkinson River and Arafura swamp.

2 Program development

On 2 May 1990 an inter-agency meeting was held in Canberra to address the need for an effective and efficient long-term program to control mimosa in the Northern Territory. As the eastern and western extremities of mimosa are on Aboriginal land, a proposal was developed to control mimosa on all Aboriginal land in the Northern Territory.

A Public Environment Report was completed in April 1991 entitled 'Proposal to control *Mimosa pigra* on Aboriginal land in the Northern Territory by chemical and mechanical methods' (Anon 1991). The Commonwealth Department of the Arts, Sport, the Environment, Tourism and Territories (DASETT) invited public submissions on this proposal and an 'Environment Assessment Report' supporting the proposal with certain recommendations was published in June 1991.

Funding for 1991-92 was achieved with a specific grant. This funding was only for the Oenpelli area for one year. A component of funding was to be used for environmental research and monitoring of the program. The program included aerial application of herbicides and ground control of isolated plants. In 1992–93 reduced funds meant that only the leading edge could be treated and the ground teams employed. In 1993–95 the total area was again treated.

An inter-agency Steering Committee has prime responsibility for the program which is implemented by the Weeds Branch of DPIF. The Committee comprises one officer from each of the Department of the Environment, Sport and Territories (DEST), the Australian Nature Conservation Agency (ANCA), the Commonwealth Scientific and Industrial Research Organisation (CSIRO), NLC (Chairman), DPIF, the Conservation Commission of the Northern Territory (CCNT) and the Northern Territory Department of Health.

Preparation of the area was originally developed using 1 to 20 000 colour aerial photographs. This allowed access tracks, marking tracks and areas for ground control to be laid out. A total of 50 km of tracks was made to allow ground marking for aerial application. Measurement of the area was further developed with Landsat TM and GPS Data. This allowed the area to be divided into sections for project management (table 1).

3 Control program

Under the terms of the Public Environment Report five herbicides were available for use. These are tebuthiuron (Graslan 20P®), fluroxypyr (Starane®), metsulfuron methyl (Brush-Off®) dicamba (Banvel 200®) and hexazinone (Velpar®).

Timing of application is critical for the application of these herbicides. Graslan is applied first and needs to be applied before the floodplain becomes wet but after the risk of fires is reduced. It was originally thought that cracks in the black soil would allow pellets to disappear down the soil profile and so be lost. It has subsequently been shown that there is no advantage in applying Graslan to sealed soils (Batterham 1992). The application of Starane, which is used to kill scattered plants left alive after Graslan application or where this herbicide is not appropiate, requires a different approach. Time needs to be allowed for the initial Graslan application to defoliate the plant so as to avoid duplication. Mimosa needs to be actively growing to translocate the herbicide but application should be carried out before the plants set seed.

The application of herbicides to such a large dense stand requires the use of aircraft. Due to the isolated nature of the program and lack of appropriate airstrips helicopters are used. Due to the need to transport through Kakadu National Park a trailer suitable for containers was purchased to minimise the chance of spillage in an accident. Original marking in 1988 was carried out by walking with a flag on a pole. This was refined to poles on Toyota 4x4 vehicles, then flashing lights on bulldozers and now a fully electronic system using a differential GPS and onboard computers is being developed.

Table 1 Aerial herbicide application in hectares on the Oenpelli floodplain

BAY	HERBICIDE	1991-92	1992-93	1993-94	1994-95	CONTROL
Plain	Graslan	0	0	63	83	Finished
	Starane	25	131	35	24	
Stripy	Graslan	1227	59	144	0	Finished
	Starane	109	67	20	123	
Sick	Graslan	1424	774	47	44	Finished
	Starane	212	403	363	269	
North	Graslan	1593	168	1616	1167	Finished
	Starane	407	0	66	74	
East/South	Graslan	2803	0	1710	1145	Finished
	Starane	318	0	224	216	
Sandy	Graslan	962	107	1019	0	Finished
	Starane	238	178	182	328	

Difficulties with marking and calibration of the only available Isolair® Graslan applicator meant that following striping in year one considerable recalibration was required. This was completed and now an even application can be achieved, provided limitations with flight separation and meteorological requirements are met. Foliar applications have been carried out since 1988 with few problems.

The key to mimosa control is to break the cycle of seed production (Miller 1988). Ground control of isolated plants has been a key aspect of the program (Miller & Schultz 1993). The employment of local workers has proved successful. Several have worked on the program for a number of years.

4 Revegetation

Old stands of mimosa out-compete most floodplain species. The use of herbicides on mimosa can also reduce other non-grass species (Cook 1992). Therefore the killing of mimosa is only the first stage in returning to the pre-mimosa ecosystem. Following treatment, mimosa is generally chained with bulldozers capable of negotiating floodplains. The area is then burnt. Mimosa is fire resistant (Lonsdale & Miller 1993) and chaining will enhance burning. Even then, a complete burn is rarely achieved. The use of a helitorch helps achieve a more complete burn. Burning removes the mimosa trash and allows access for the ground team. Fire also increases the germination of the mimosa seed bank so that seedlings can be controlled in the next season.

There is little information available on the natural vegetation of the Oenpelli floodplain, but it is known that para grass occurred in the vicinity. Before mimosa invaded the area it carried large numbers of buffalo, and overgrazing probably contributed to the mimosa expansion in the first place. The use of herbicides also have an effect on other vegetation. Melaleuca trees have been killed in sections of the floodplain margins, however in treated areas, the diversity of native herbaceous species is greater than in untreated areas (Cook 1992). Two species, common in similar habitats nearby, could not be found after initial clearing. These were hymenachne (*Hymenachne acutigluma*) and wild rice (*Oryza rufipogon*). A technique was developed to harvest these species from the Mary River floodplain for use on the Oenpelli project. In 1993 both species were harvested and sown. In 1994 hymenachne failed to set seed. This occurred over several areas, and the only sample found with viable seed was a sample hand harvested at Yellow Waters in Kakadu. Wild rice produced seed in both seasons. The variable nature of seed production from hymenachne is of concern and needs investigation. The establishment of these species in an area cleared of mimosa is also proving difficult and requires detailed study.

5 Conclusion

This was the largest application of herbicide ever undertaken in the Northern Territory, the largest application to mimosa in the world, the largest Graslan application in Australia and probably the largest single application of Graslan to a wetland environment in the world. Techniques have been developed to allow selected herbicides to be applied in an acceptable manner. Mimosa can be controlled provided a long term approach is taken. The large scale aerial application of herbicides will be finished in 1996 but the success of the program depends on the continuation of ground control for many years. It is hoped that successful biological control is eventually achieved so that such large applications of herbicide are no longer required. Even so, the restoration of floodplains through reintroduction of either introduced or native species needs to be developed and refined.

6 References

Anon 1991. *Proposal to control* Mimosa pigra *on Aboriginal Land in the Northern Territory by chemical and mechanical methods.* Public Environment Report, Northern Land Council.

Batterham GJ 1992. *Dissipation and degradation of the urea herbicide Tebuthiuron in Northern Territory floodplain environments.* B. Sc. Hons. Thesis, Northern Territory University.

Cook GD 1992. *Control of* Mimosa pigra *at Oenpelli: Research and Monitoring Program.* Preliminary report to the Steering Committee of the program to control mimosa on Aboriginal lands in the Northern Territory. CSIRO Division of Wildlife and Ecology, Darwin.

Lonsdale WM & Miller IL 1993. Fire as a management tool for a tropical woody weed: *Mimosa pigra* in Northern Australia. *Journal of Environment Management* 39, 77–87

Miller IL 1988. Aspects of the biology and control of *Mimosa pigra* L. M.Sc.Agr. Thesis, University of Sydney.

Miller IL & Lonsdale WM 1987. Early records of *Mimosa pigra* in the Northern Territory. *Plant Protection Quarterly* 2, 140–142.

Miller IL & Schultz GC 1988. Recommendations for the control of *Mimosa pigra* in Arnhem Land. Unpublished Report, Department of Industries and Development Darwin.

Miller IL & Schultz GC 1993. *The management of weeds on Aboriginal land with special reference to* Mimosa pigra. Proceedings 1, 10th Australian Weeds Conference and 14th Asian-Pacific Weed Science Society Conference, Brisbane, Australia, 6-10 September 1993.

ECOSYSTEM DYNAMICS AND THE MANAGEMENT OF ENVIRONMENTAL WEEDS IN WETLANDS

G COOK & S SETTERFIELD

CSIRO Division of Wildlife and Ecology
PMB 44, Winnellie, NT 0821

ABSTRACT

We developed a conceptual state-and-transition model of ecosystem dynamics for the sub-coastal floodplains of the Northern Territory. This model showed the possible transitions between three major ecosystems of the floodplains; native grassland/sedgeland, exotic grassland, and Mimosa *shrubland. We used this model to systematise existing knowledge of the dynamics of these ecosystems, and identified several areas of research opportunity to facilitate better management These research areas included: (1) management strategies to limit weed invasion; (2) control of grassy weeds; (3) post-treatment restoration; and (4) off-site impacts of invasive species.*

Keywords: weeds, integrated management, *Mimosa pigra, Brachiaria mutica*, wetlands

1 Introduction

The sub-coastal wetlands of the NT are an important resource for nature conservation (Finlayson et al 1988), but their integrity has been compromised by weed invasions. Mimosa (*Mimosa pigra*) has invaded at least 800 km² of wetlands (Lonsdale et al 1989) and Para Grass (*Brachiaria mutica*) has also invaded substantial areas including several thousand hectares on the East Alligator River floodplain (Cowie & Werner 1993). While *Mimosa* is a declared noxious weed in northern Australia, Para Grass is being promoted as an improved pasture species to replace the native wetland communities in pastoral areas.

Wetland managers need to be aware of the latest developments in weed control. Unfortunately, several recent reviews of research directions for weed science failed to mention weeds of conservation, but focussed mainly on agricultural weeds (Coble 1994, Hess 1994, Bridges 1994, Liebman & Dyck 1993). Nevertheless, much can be learnt from the trend towards systems approaches that integrate various control techniques with sound land management practices (eg Hess 1994). Although such strategies have been recommended for the control of weeds of conservation (Humphries et al 1991), a greater understanding of ecological processes is required because the desired natural ecosystems are vastly more complex than a sown monoculture.

An appropriate framework for systematising research issues posed by weeds of conservation could be provided by state-and-transition (SAT) models of ecosystem dynamics. These SAT models emphasise the role of climatic events and management actions in causing transitions between ecological states (Westoby et al 1989). They provide a framework for recognising circumstances that favour particular transitions so that appropriate action can be taken. SAT models should be appropriate where substantial changes in vegetation structure or function can occur. In this paper, we apply a conceptual SAT model of ecosystem dynamics to the wetlands of northern Australia as a means of systematising existing knowledge. This allows gaps in the knowledge of weed control and land management in the wetlands to be identified.

2 The proposed SAT model of wetland dynamics for northern Australia

The state-and-transition model proposed for these wetlands incorporates four ecological states and six possible transitions between them (figure 1). Based on the limited research into the attributes of the various ecological states (eg Braithwaite et al 1989, Miller et al 1981, Tulloch & Cellier 1986, Foran et al 1990), the state-and-transition model was located in a space defined by two axes; one of increasing conservation value, and the other of increasing pastoral profitability. These axes provide a notional assessment of the relative impacts of particular transitions on two major land uses in this region.

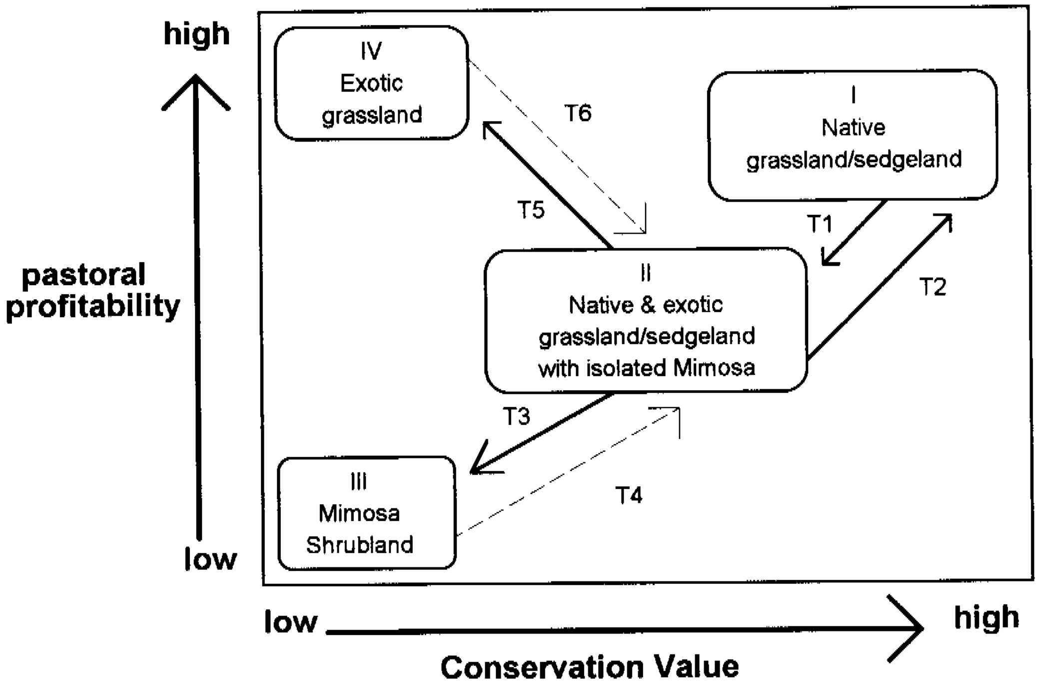

Figure 1 A state-and-transition model of ecosystem dynamics in the wetlands of northern Australia. Dotted lines indicate transitions that can only be achieved by major restoration works

State I, a pristine native wetland, is arguably a conceptual goal of management that can never be reached. Scattered outbreaks of exotic species will always be present so that the practical goal of management in conservation areas will be State II. The boundaries between areas of land allocated to these two states are scale dependant. For example, the density of *Mimosa* outbreaks in various wetlands of Kakadu National Park until 1993 was between 0.04 km^{-2} and 0.2 km^{-2} (Cook et al in press). This low density leaves ample areas of land that could be deemed as 'pristine' wetlands if exotic herbaceous species are ignored, but for management purposes, the entire area of wetlands in the Park is best considered as having some *Mimosa* outbreaks and being in a non-pristine state. A similar argument would be true for invasive herbaceous species. The non-pristine status of State II would be acceptable for conservation purposes provided that this low density of exotic plants has little effect on ecosystem function and appropriate management ensures that the likelihood of transitions to *Mimosa* shrubland (state IV) or other exotic-dominated systems remains low.

3 Issues for research and management

3.1 Setting the management goal

The management goal when applying state-and-transition models, is to maintain or establish a desired ecosystem under a regime of continually changing opportunities and hazards which allow transitions between alternative ecological states. The first step is to define the ecological states and the possible transitions between them. Only then can the desirability of particular alternative states be considered properly. For some states, such as *Mimosa* shrubland, the desirability or otherwise may be readily apparent to all, but for others, such as exotic grassland, it may be subject to debate. We have proposed that placing the possible ecological states on a plane defined by axes of pastoral profitability and conservation value is appropriate for understanding ecosystem dynamics in a multiple-use area of northern Australia. Accurate placement of ecological states, based on appropriate research, will help in the resolution of conflicts in the definition of undesirable ecological states and therefore in the definition of weeds on multiple-use lands. Ecological states where both the conservation value and the pastoral profitability are relatively high should produce the greatest benefit to society as a whole.

3.2 Developing the management strategy

Avoiding undesirable transitions

Research into the various ecological transitions has focussed particularly on the establishment and spread of *Mimosa* (transitions 1 & 3: Lonsdale 1993, Lonsdale et al 1989, Cook et al in press). In contrast, there has been almost no research into the unassisted spread of Para Grass which occurs in transitions 1 and 5 (Cowie & Werner 1993), but the active establishment of exotic pasture grasses which tolerate flooding has received considerable attention (Coffey 1991).

The control of satellite outbreaks of a weed is clearly critical to avoiding undesirable transitions (Moody & Mack 1988), but perhaps of greater importance is the development of land management practices which maintain a resilient ecosystem and are sensitive to the climatic triggers for weed invasion. In the present case study, the management of introduced cattle, buffalo and pigs is of crucial importance. Disturbance by feral buffalo and pigs is recognised as an important precursor to weed invasion (Cowie & Werner 1993, Lonsdale 1993) and feral buffalo have now been eradicated to a large extent. Nevertheless, commercial grazing of domestic buffalo and cattle is increasing, but little attention has been given to the development of strategies that could prevent further weed invasions such as conservative grazing or the possible role of fire management which can prevent woody weed establishment in other systems (Hodgkinson 1990). The role of disturbance by introduced mammals on the establishment of *Mimosa* stands is likely to be greater after seasons of high rainfall (Lonsdale 1993).

Encouraging desirable transitions

To return land invaded by an environmental weed to a desirable ecological state requires firstly an integrated program of biological, chemical and mechanical weed control. However, without an adequate strategy of post-treatment restoration coupled with sensitive management of the restored land, land managers may be ill-prepared when biological or other control tactics become successful (Buchanan 1988). It is quite possible that re-invasion could occur or one weed may simply replace another (Hobbs & Mooney 1993). In northern Australia, Para Grass and other exotic grasses may invade many areas formerly occupied by *Mimosa* and may prove to be more intractable wetland weeds than *Mimosa*.

Research into the restoration of native wetland ecosystems has focussed on the biological, chemical and mechanical control of large stands and satellite outbreaks of *Mimosa* (transitions 4 & 2: see Harley 1992). In contrast, there has been almost no work on the control of exotic pasture species such as Para Grass (transitions 6 & 2). The re-establishment of native vegetation after the control of *Mimosa* or Para Grass is a major aspect of restoration which has received little attention. Exotic pasture species have been shown to out compete *Mimosa* (Miller 1992, Miller & Lonsdale 1992), which suggests that exotic grasses may dominate the wetlands if disturbance continues in the presence of propagules of *Mimosa* and exotic pasture species.

3.3 Some specific research topics

To be a useful tool in wetland management, the state-and-transition model will require further quantification of the attributes of the ecological states. Additional SAT models will need to be developed, or refinements added as the knowledge base expands and other wetland systems such as *Melaleuca* forests are considered. The review of existing knowledge has shown that some of the transitions between states are poorly understood. Some specific research topics which address these gaps in the knowledge are listed below:

Maintaining resilient wetlands

- appropriate management for commercial grazing of cattle and buffalo
- enhanced control of feral pig damage
- the use of fire to prevent woody weed encroachment

Control of grassy weeds

- appropriate timing of control efforts
- use of chemical, mechanical (including fire) and biological controls
- economics of pasture improvement in regional economy
- possible use of sterile cultivars for pastoral improvement
- competition between native and exotic species

Post-treatment restoration

- rates of vegetation re-establishment
- effects on fauna
- requirement for assisted revegetation in different landscapes
- development of appropriate techniques for assisted revegetation
- cost-effective removal of dead or debilitated *Mimosa*

Off-site impacts of invasive species

- effects of loss of habitat on mobile fauna such as Magpie Geese
- potential for spread of exotic grasses from pastoral lands to conservation or other wetlands

4 Conclusions

We conclude that agricultural concepts of integrated weed control, while valuable, are insufficient for the management of environmental weeds because they still focus on weed control as the primary goal. Although appropriate for agricultural lands, this emphasis would result in the crucial issue of post-treatment restoration being given inadequate attention in a research plan for conservation areas. The potential would then exist for another undesirable ecological state to replace the one initially targeted. The goal for the management of weeds of conservation must be seen as the maintenance of a desirable ecological state and research must be directed towards that goal. In this context, the control of satellite outbreaks and large stands of weeds are just additional tools in achieving the goal along with post-treatment restoration and management to avoid weed invasion. By bringing attention to the effects of management and climatic events on ecosystem dynamics, state-and-transition models provide a useful framework for setting research agendas and management strategies for the control of weeds of conservation in Australia's northern wetlands.

Acknowledgments

We would like to thank Mark Lonsdale, Alan Andersen, Dick Braithwaite and Michael Douglas for helpful comments on the manuscript.

5 References

Braithwaite RW, Lonsdale WM, & Estbergs JA 1989. Alien vegetation and native biota in tropical Australia: the spread and impact of *Mimosa pigra*. *Biological Conservation* 48, 189–210.

Bridges DC 1994. Impact of weeds on human endeavors. *Weed Technology* 8, 392–395.

Buchanan RA 1988. Bush regeneration: recovering Australian landscapes. TAFE Student Learning Publications, Sydney.

Coble HD 1994. Future directions and needs for weed science research. *Weed Technology* 8, 410–412.

Coffey SG 1991. Historical perspectives, current status and current construction guidelines for ponded pastures in Queensland: Overview paper. In *Proceedings of Probing Ponded Pastures Workshop, July 1991*, University of Central Queensland, Rockhampton.

Cook GD, Setterfield SA & Maddison JP (in press). Shrub invasion of a tropical wetland: Implications for weed management. *Ecological Applications*.

Cowie ID & Werner PA 1993. Alien plant species invasive in Kakadu National Park, tropical northern Australia. *Biological Conservation* 63, 127–135.

Finlayson CM, Bailey BJ, Freeland WJ & Fleming MR 1988. Wetlands of the Northern Territory. In *The conservation of Australian wetlands,* (eds) AJ McComb & PS Lake, Surrey Beatty and Sons Pty Ltd, Chipping North, 103–126.

Foran BD, Stafford Smith DM, Niethe G, Stockwell T & Michell V 1990. A comparison of development options on a northern Australian beef property. *Agricultural systems* 34, 77–102.

Harley KLS 1992. *A guide to the management of* Mimosa pigra. CSIRO, Canberra.

Hess FD 1994. Research needs in weed science. *Weed Technology* 8, 408–409.

Hobbs RJ & Mooney HA 1993. Restoration ecology and invasions. In *Nature conservation 3: Reconstruction of fragmented ecosystems,* (eds) DA Saunders, RJ Hobbs & PR Ehlich, Surrey Beatty & Sons, 127–133.

Hodgkinson KC 1990. The ecological basis of prescibed burning for shrub control in the semi-arid pastoral zone of Australia. In *Proceedings of the International Symposium on Grassland Vegetation*, (ed) X Hanxi, Science Press, Beijing, China, 557–564.

Humphries SE, Groves RH & Mitchell DS 1991. Plant invasions: The incidence of environmental weeds in Australia. *Kowari* 2, 1–134.

Liebman M & Dyck E 1993. Weed management: a need to develop ecological approaches. *Ecological Applications* 3, 39–41.

Lonsdale WM 1993. Rates of spread of an invading species: *Mimosa pigra* in northern Australia. *Journal of Ecology* 81, 513–521.

Lonsdale WM, Miller IL & Forno IW 1989. The biology of Australian Weeds 20. *Mimosa pigra* L: *Plant Protection Quarterly* 4, 119–131.

Miller IL 1992. Competition between *Brachiaria humidicola* and *Mimosa pigra*. Tropical Grasses 26: 111–114.

Miller IL, Nemestothy L & Pickering SE 1981. *Mimosa pigra* in the Northern Territory. Northern Territory Department of Primary Production, Division of Agriculture and Stock, Technical Bulletin No. 51.

Miller IL & Lonsdale 1992. Ecological management of *Mimosa pigra*: use of fire and competitive pastures.In Harley KLS (ed) A guide to the management of *Mimosa pigra*, CSIRO, Canberra.

Moody ME & Mack RN 1988. Controlling the spread of plant invasions: The importance of nascent foci. *Journal of Applied Ecology* 25, 1009–1021.

Tulloch DG & Cellier KM 1986. Grazing behaviour of feral buffaloes on a native pasture in the northern portion of the Northern Territory. *Australian Wildlife Research* 13, 433–439.

Westoby M, Walker BH & Noy-Meir I 1989. Opportunistic management for rangelands not at equilibrium. *Journal of Range Management* 42, 266–274.

PONDED PASTURES: A THREAT TO WETLAND BIODIVERSITY

J CLARKSON

Queensland Department of Environment and Heritage,
PO Box 1054, Mareeba, Queensland 4880

ABSTRACT

The introduction of the exotic aquatic grasses Hymenachne amplexicaulis *and* Echinochloa polystachya *as pasture grasses has been the subject of much controversy. The spread of these grasses beyond the pasture system into freshwater wetlands poses a potentially serious threat to the long term viability of many aquatic species. Factors contributing to the risk of spread are discussed. The potential for dispersal of undesirable aquatic weeds, pathogens or animal pests in planting material is highlighted. There is an urgent need for research to address the issues raised so that an objective policy towards the continued promotion of these grasses or the introduction of further species can be formulated.*

Keywords: ponded pastures, aquatic weeds, plant introductions, para grass, *Hymenachne amplexicaulis, Echinochloa polystachya, Brachiaria mutica*

1 Introduction

In the seasonally wet/dry tropics cattle weight losses associated with the declining nutritional value of native pastures as the dry season progresses is one of the major factors limiting productivity. Pasture agronomists have concentrated a major part of their research effort on ways of reducing these dry season weight losses. The cornerstone of their efforts has been introduced pasture species and will probably remain so. However, observations that the green grass in naturally occurring gilgais and swamps provided reasonable forage in the dry season led some enterprising primary producers to attempt to extend the growing season by undertaking earthworks designed to restrict runoff and to pond water in shallow depressions (Wildin 1991). Para grass (*Brachiaria mutica* (Forssk.) Stapf), a native of tropical Africa and South America, which had been introduced into Queensland in the late 1880s for erosion control on stream banks (Barnard 1969), was found to grow well in the shallow water ponded in this way. However, this grass will not grow in water much deeper than 50-60 cm and the high evaporative losses from such shallow ponds limits the areas where the grass can be effectively used (Kernot 1991).

In the 1930s a few graziers in the Central Queensland area began to construct earth banks on the coastal plains around St Lawrence and Stanage Bay, just north of Rockhampton, to prevent the encroachment of saltwater at high tides. Freshwater trapped behind these banks promoted the growth of aquatic plants. Para grass in particular grew well in these areas. Until the 1970s this pondage was driven largely by the initiative of individual producers and was fairly limited in its extent. About this time the Queensland Department of Primary Industries (QDPI) began to promote the technology and it became more widely adopted (Wildin 1991). To date close to 22 000 ha of grazing land has been ponded in the central Queensland area alone (Coffey 1991). Commercial fisherman began to become concerned about what effects this alienation of large areas of marine plains could be having on fish stocks in the area. A heated, public debate between fisherman and graziers developed. The media became involved and pictures of large barramundi stranded in drying ponds behind the sea walls inflamed the situation. However, rather than simply causing the deaths of a few mature fish, the effects are more subtle and relate to the role the marine plains play as nursery areas and refuges for the juvenile stages of many estuarine species and as a nutrient source for the adjacent estuarine area (Garrett 1991). The situation was partly resolved, at least as far as the commercial fisherman were concerned, when the Queensland Minister for Environment and Heritage declared a moratorium on further sea wall construction following a workshop on ponded pastures held in Rockhampton in 1991.

Associated with QDPI's support and promotion of ponded pastures was the introduction of two grasses of South American origin, *Hymenachne amplexicaulis* (Rudge) Nees and *Echinochloa polystachya* (Kunth) Hitchc. These grasses are similar in their habitat requirements to para grass but are able to grow in water up to one metre deep - almost twice the maximum depth tolerated by para grass (Oram 1990). This means that deeper ponds can be constructed to help overcome the high water losses due to evapotranspiration and has lead to pondage being promoted across a wider area of tropical Queensland well removed from the marine plains (Kernot 1991).

It is this expansion of the area where pondage is being promoted and suggestions that more species be introduced in the face of warnings of the risks associated with the potential for spread of the existing species which has promoted a growing concern in Queensland that pondage species may become serious environmental weeds.

2 Inherent risks in introduced pasture species

Associated with the introduction of any species, native or exotic, outside of its natural range, is the risk that the plant will spread beyond the place of introduction. This is used to advantage by pastoralists to establish introduced pasture species under rangeland conditions. While this is a legitimate land use in areas set aside for grazing, it can lead to serious conflicts of interest when the plant spreads beyond the grazing system (target areas) to areas where grazing is not the primary land use (non target area), eg cropping areas, urban areas, conservation reserves, etc. Many of the ecological problems posed by introduced species in Australia have stemmed from a failure to recognise this conflict of interest and to adequately weight the cost of habitat degradation and control in non target areas against the benefits which prompted the introduction. In years past, when many of the ecological concepts we take for granted now were simply not understood perhaps some of these introductions can be excused. Given our present knowledge of the often complex interrelationships which exist in nature and the value the community places on the environment, the time has come to give more detailed consideration to such matters prior to introduction or release.

Pasture scientists are faced with the dilemma that many of the desirable characteristics of pasture species predispose the plants to behave as weeds. Firstly the species must be able to establish following sowing into areas where often little or no seedbed preparation is possible. Secondly, they have to disperse and establish away from the place where they were sown. Finally, the plants have to be able to persist under harsh environmental conditions, survive grazing pressures and remain competitive. It is impossible to have a grazing industry dependant on introduced species and not live with some of these risks, however the risks are not uniform from species to species. For some species the benefits may outweigh the risks, for others the risks may simply be too great. The plants utilised for ponded pastures differ from most other pasture species in that they are adapted to exist in an aquatic environment where the risk of spread is exceptionally high.

3 Why are pondage species and aquatic systems different

Introduced aquatics have a particularly bad record of spread in Australia. Most of the species which have become particularly troublesome weeds were introduced initially for aquarium or horticultural use. These include *Alternanthera philoxeroides* (Mart.) Griseb. (Alligator Weed), *Salvinia molesta* DS Mitch. (Salvinia), *Eichhornia crassipes* (Mart.) Solms (Water Hyacinth) and *Mimosa pigra* L. (Giant Sensitive Plant). *Brachiaria mutica* (Para Grass), the only ponded pasture species to have been introduced sufficiently long ago, has become a widespread weed in coastal Queensland. There is no evidence to suggest that the more recently introduced ponded species will not follow a similar pattern.

In aquatic situations a failure to set seed is no impediment to spread. Flooding can break plants into small pieces which are then swept downstream to colonise new areas. Severe flooding also tends to disturb stream bank vegetation thus reducing competition from native plants as the newly arrived introduction attempts to become established.

While seed of *Brachiaria mutica* and *Hymenachne amplexicaulis* is commercially available, most plantings of ponded pastures in Queensland utilise vegetative material. Large quantities of runners are often transported over long distances with the attendant risk of carrying aquatic weeds, pathogens or animal pests between catchments. Examples are known of runners being sent from Far North Queensland to the Broome area in Western Australia.

4 Possible effects of spread of pondage species

It is difficult to accurately predict what effects might stem from a spread of introduced deep water grasses to non target areas. A worst case scenario might see environmental effects equal to, or perhaps worse than, those caused by para grass. The ability of the newer grasses to grow in much deeper water than para grass supports the latter.

Given fairly uniform substrate, water quality and flow rates, water depth is perhaps the single most important factor governing the distribution of aquatic plants within a single water body. Variation in depth provides niches which can be colonised by a range of species. This variation is greatest around the margins and therefore it is here that the greatest diversity of plants and the animals which are dependent on them is found. This is the area which will be colonised by the pondage grasses.

As native species are displaced, species diversity falls. Few native rooted aquatic plants could survive in water too deep to sustain either *Hymenachne amplexicaulis* or *Echinochloa polystachya*. As the diverse assemblage of plant life around the margin is replaced by a monospecific stand of grass many of the animals which are dependant on these areas for food and shelter are forced to move elsewhere. Not all animals will be affected in the same way, some may even be favoured by the presence of dense stands of grass. In general though more species are likely to be disadvantaged than favoured. In areas set aside primarily for nature conservation such shifts in the balance of species is undesirable.

5 Differing views of plant establishment

Following introduction of ponded pasture species, the measure of successful establishment will vary depending on the viewpoint of the observer. From a producers perspective establishment will probably be rated as unsuccessful if the end product of introduction is not a productive pasture, that is, unless there is a significant increase in the biomass of the introduced species compared with that planted. The pasture will also have to persist and maintain productivity from season to season under prevailing environmental conditions and the pressures of grazing.

From a biological view this quantum increase in biomass following introduction is not essential for establishment to be rated successful. Even if only a small fraction of the initial planting material survives from season to season the plant can be judged to have become established. The continued presence of the plant, even if only in small numbers, provides a source of propagules which may be carried to other localities. Under rangeland conditions there are many examples of introduced species which have remained present in small numbers and localised in occurrence for many years before spreading and becoming weedy. The catalyst for spread has often been an infrequent natural event such as wildfire, drought, flooding or a succession of wet years. Overgrazing or a change in management practices (eg switching from sheep to cattle) also have the potential to initiate spread. The trigger in the case of introduced ponded species is likely to be flooding and this is far from an infrequent event in many areas being explored for ponded pastures in the Far North.

Having made this distinction, it is obvious that reports from producers or pasture agronomists of failed attempts to establish ponded pastures in certain areas cannot necessarily be taken to mean that the species is absent from the catchment. It also suggests that care should be taken in using the experiences of producers in an attempt to establish where the deep water pondage species might or might not be likely to establish under natural conditions. Given the scanty information available in the literature this is likely to be attempted.

6 Additional species for ponded systems

Additional species have been suggested which might have potential for use in ponded systems (Wildin 1985). Some of these are listed in table 1.

Table 1 Species suggested for introduction and evaluation for pondage systems

SPECIES	COUNTRY OF ORIGIN
Brachiaria radicans Napper	Tropical Africa
Echinochloa haploclada (Stapf) Stapf	Tropical Africa
Echinochloa pyramidalis (Lam.) Hitchc. & Chase	Tropical Africa
Echinochloa stagnina (Retz) Beauv.	Tropical Africa, parts of Asia, Philippines
Entolasia imbricata Stapf	Tropical Africa
Eriochloa meyeriana (Nees) Pilget	Tropical Africa
Eriochloa punctata (L.) Desv. ex Hamilt.	Tropical and subtropical America, West Indies
Hymenachne pseudo-interrupta C. Muell.	Indo-Malaya
Leersia denudata Launert	Africa
Panicum elephantipes Nees	Tropical and sub-tropical America
Vossia cuspidata (Roxb.) Griff.	Africa

Wildin (1985) targeted four species in particular, *Echinochloa stagnina*, *Eriochloa meyeriana*, *Panicum elephantipes* and *Vossia cuspidata* for early introduction and evaluation in artificially ponded systems. *Echinochloa pyramidalis, Entolasia imbricata, Eriochloa meyeriana* and *Eriochloa punctata* have been introduced. With the introduction of further species the risk that eventually one of the introduced ponded species will become invasive in non target areas increases. *Echinochloa stagnina*, one of the suggestions for early introduction, was one of 23 species listed by Michael (1989) as a weed of potential Quarantine concern to northern Australia. *Panicum elephantipes* has the ability to form floating meadows and *Vossia cuspidata* can be a nuisance in irrigation canals and ditches. Despite this, in proposing the introduction of these grasses Wildin (1985) stated, '*these grasses have never been reported to be weeds in lakes, streams and rivers where they originate*' and '*they are unlikely to be objectionable in Australia*'. Past experience has shown that weedy introduced species seldom behave as weeds in their native habitat. Can this apparent dismissal of the risk of spread or a failure to adequately review the literature pertaining to proposed introductions be condoned? This example serves to highlight the need for more careful review of species prior to introduction.

7 Controls on plant introductions

For a number of years there have been calls from certain sections of the agricultural community, primarily those involved with weed research, for stricter guidelines to be applied to the introduction of crop, pasture and ornamental plants into Australia. These calls have largely gone unheeded. While strict sanctions apply to the introduction of biological control agents, most plant introductions encounter few if any barriers and enter the country with little consideration of benefits or costs. This constitutes a serious inconsistency in import regulations. A number of screening protocols have been suggested (Hazard 1988, Lonsdale 1994). Each attempts to restrict the entry of potential weeds by placing the onus on the importing agency to prove that the species will not be weedy and/or result in a net financial or ecological gain to the nation prior to receiving approval for introduction or release.

8 Conclusions

Based on the demonstrated behaviour of introduced aquatics it is highly likely that the deep water grasses *Hymenachne amplexicaulis* and *Echinochloa polystachya* will spread beyond the pasture system. The likely impact of the spread is difficult to predict with accuracy and the debate between opponents and proponents of ponded pastures rages on with no substantiated evidence to support either case. Only once this evidence is available will it be possible to formulate an objective policy towards the continued promotion of these grasses or the introduction of further species. Some experimental studies on *Hymenachne amplexicaulis* are underway at the University of Queensland, Gatton (P Pittaway pers comm) but a great deal more needs to be done to assess the dispersal, establishment and competitive ability of pondage species in the aquatic environment.

Finally, if this process is not to be repeated over and over again, there is an urgent need for a redefinition of the policies on plant introduction. This should review the procedures for plant introduction (both legal and illegal) in the light of factors associated with release and escape, promotion, control and eradication of introduced plants.

9 References

Barnard C 1969. *Herbage Plant Species*. Australian Herbage Plant registration Authority, CSIRO, Canberra. pp. 12–15.

Coffey SG 1991. Historical perspectives, current status and current construction guidelines for ponded pastures in Queensland: Overview paper. In *Proceedings of the Ponded Pasture Workshop*, Rockhampton, 16–18 July 1991.

Garrett RN 1991. Utilization of wetland habitats by coastal fishes in Northern Australia. In *Proceedings of the Ponded Pasture Workshop*, Rockhampton, 16–18 July 1991.

Hazard WHL 1988. Introducing crop, pasture and ornamental species into Australia: The risk of introducing new weeds. *Australian Plant Introduction Review* 19 (2), 19–36.

Kernot JC 1991. The current status and potential of ponded pastures in North Queensland. In *Proceedings of the Ponded Pasture Workshop*, Rockhampton, 16–18 July 1991.

Lonsdale WM 1994. Inviting trouble: Introducing pasture species in Northern Australia. *Australian Journal of Ecology* 19, 345–354.

Oram RN 1990. *Register of Australian Herbage Plant Cultivars.* third edn, CSIRO, Australia.

Michael PW 1989. Review paper on weeds of quarantine concern to Northern Australia. Report prepared for the Department of Primary Industries and Energy, Canberra.

Wildin JH 1985. Tropical grasses for ponded pastures. Mimeographed report, Queensland Department of Primary Industries, Rockhampton.

Wildin J 1991. History of ponded pastures in Queensland. In *Proceedings of the Ponded Pasture Workshop*, Rockhampton, 16–18 July 1991.

A REVIEW OF NORTHERN TERRITORY WETLAND RAINFALL: CURRENT AND PROJECTED

I BUTTERWORTH

Bureau of Meteorology, GPO Box 735, Darwin, NT 0801

ABSTRACT

Predicting regional climate change under a warmer atmosphere scenario is not simple. It requires knowledge and understanding of many factors including: the current (or equilibrium) conditions; possible feedback mechanisms (positive and negative); land-sea interaction; topography; forestation etc; and the development of improved higher resolution models which includes adequate descriptions of all components of the climate system.

This review is a collation of current understanding relating to the equilibrium and simulated warmer climate conditions of rainfall over the Northern Territory wetlands. It is noted that: average annual rainfall will increase by around 20% and that its seasonality will be maintained; rain day numbers will be marginally higher and rainfall intensity is expected to increase; and there is evidence to suggest tropical cyclones will not be more intense but a stronger monsoon may occur.

Keywords: warmer atmosphere, rainfall, simulated climate, seasonality, rainfall intensity, monsoon, cyclic nature of the wet season, tropical depressions over the Northern Territory.

1 Introduction

The simulated effects of global climate change resulting from anthropogenic greenhouse gases is one of great scientific complexity. General circulation models (GCMs) are the most important source of information, however, simulations from model to model are not always consistent, especially at regional levels. For example, it is not unusual for the change in precipitation given by two models for a particular region to differ in sign (Whetton & Pittock 1991).

Current scientific understanding predicts global warming in the next few decades with a high degree of probability. The results of GCMs suggest that by doubling the atmospheric carbon dioxide (CO_2) concentration from its pre-industrial level, the resultant increase in mean surface air temperature would lie in the range 1.5–4.5°C (Annual Report 1994). The major challenge however is to translate these global predictions to a regional level. Regional consequences of a warmer earth under an enhanced greenhouse effect become vital since we cannot infer that the climate of every region will be the same. Furthermore, the impact of a warmer earth will vary depending on magnitudes of changes of particular climatic elements.

The prediction of future climate change is critically dependent on scenarios of future anthropogenic emissions of greenhouse gases and other climate forcing agents such as aerosols. Notwithstanding this complexity, most models are run to an equilibrium for present levels of only one greenhouse gas, carbon dioxide (1 x CO_2), and simulate conditions under a doubling (2 x CO_2) of the present concentration. Essential to effective model simulations are good zero order conditions, that is, the basic component values used in the models must be close to those observed.

This paper discusses current and projected values of rainfall over the Northern Territory wetlands. It does not delve into possible impacts of a change in the rainfall climate, but provides a platform for further work and subsequent planning.

2 Current Climate

2.1 Seasonality

The Northern Territory Top End (a colloquial term used to describe the land mass of the Northern Territory north of 15°S) experiences pronounced wet and dry seasons. The wet season extends from October through April and is characterised by the occurrence of over 90 per cent of the annual rainfall. What is less evident, however, is the cyclic nature of the wet season. Within the wet season there are three phases:

- pre- and post-monsoon periods (transition periods), characterised by isolated thunderstorm activity
- active monsoon periods, characterised by widespread and often heavy rain. It is during these phases that tropical cyclones are more likely to occur
- monsoon break/inactive periods, characterised by a return to scattered thunderstorms and squalls.

The highest rainfall registrations across tropical Australia are most often associated with active phases of the monsoon. Only a small number of active phases (generally one, two or three) occur during each wet season and a quasi-periodic variation, of around 40-50 days has been identified between each phase (Madden & Julian 1971). Although a degree of regularity, commonly called the Madden-Julian Oscillation (MJO) is apparent, it should not always be assumed: higher frequency oscillations are occasionally observed to be superimposed on the MJO - a feature of the 1993–94 wet season. Butterworth and Arthur (1993) identified oscillations of wet and dry periods of the order of decades and Taylor and Tulloch (1985), while emphasising the reliability of north Australian rainfall, illustrated a variability in extreme events.

Inactive phases are those periods between the active phases, and transition phases are the periods leading into the first and after the final active phases respectively.

2.2 Thunderstorms

Thunderstorm occurrence over northern Australia has a strong seasonal bias. They are most frequent in the wet season months October to April when the essential ingredients for their development are ever present. Observational studies show that thunderstorms display maximum frequency of occurrence during the late afternoon and evening and a minimum in the mid to late morning.

Air-mass convective systems are the most frequently occurring events, and while actual numbers have not been determined, McQuade et al (in press) have suggested it is probable that many hundreds of individual systems occur in the wetland region during the course of a wet season. Rainfall from individual storms is usually brief and may be intense, however, flood causing effects are unlikely.

In a study of severe wind gust-producing thunderstorms in the Northern Territory, Gill (1993) found that such events were infrequent with only one or two occurring at any location each year. Because objective records of other phenomena associated with severe thunderstorms (tornadoes, hail of at least 20 mm diameter, or flash-flooding heavy rainfall) were not available, Gill's analysis was based only on storms producing wind gusts of 90 km/h or more. Scientific and anecdotal evidence strongly suggests that large hail and tornadoes are unlikely associates of severe storms in the Northern Territory tropics; flash-flooding and heavy rainfall however are more probable consequences.

2.3 Tropical cyclones

Tropical cyclones occurrence in the vicinity of the Northern Territory is seasonal, being limited to the period November to April. Studies have shown that on average, two tropical cyclones affect the Northern Territory each year; slightly less than that value actually make landfall.

Available records of tropical cyclones making coastal crossings in the vicinity of the Northern Territory wetlands (the Kakadu area) show it to be a rare event indeed with only eight crossings from 1827 to the end of 1992 (McQuade et al in press).

2.4 Tropical depressions

Tropical depressions are often a precursor to, or remnant of, a tropical cyclone and can occur over the oceans or land areas of the Northern Territory. They are far less devastating than their cyclone counterparts in terms of wind, but can be equally productive with rainfall. A number of extreme high rainfall events over the Northern Territory wetlands have occurred in conjunction with the passage of tropical depressions.

Using archived analyses from the Regional Specialised Meteorological Centre, Bureau of Meteorology - Darwin, as the data base, the number of tropical depressions over the wetlands for the months December to March throughout the period 1983–1991 was determined. The numbers are listed in table 1 where it is shown that the average per year is close to seven.

Table 1 Number of tropical depressions over the Northern Territory Top End wetlands during the months December to March for the period 1983-1991

Month	Year										
	1991	1990	1989	1988	1987	1986	1985	1984	1983	Total	Ave
January	3	2	4	4	2	NA	2	1	2	21	2.6
February	2	1	3	2	NA	3	1	5	1	18	2.3
March	1	3	4	2	0	1	3	NA	1	15	1.9
December	0	2	1	1	0	1	1	2	0	8	0.9
Total	6	8	12	9	2	5	7	9	4	62	6.9

Although this analysis is not especially rigorous, because cloud and rainfall conditions normally coexisting with extreme event situations can not be assumed from a chart analysis alone, the result nevertheless serves to illustrate the potential for extreme rainfall events over the Northern Territory wetlands.

2.5 Intensity

Rainfall intensity is a measure of rainfall amount over a period of time. High intensity rainfall in Northern Territory wetlands is known to be common and under certain conditions, extreme events can play an important role in ecological health, development and maintenance of the area (Taylor & Tulloch 1985).

Although air-mass thunderstorms (convective systems) normally lie at the lower end of the meteorological time-space scale, being around 10 sq km in area and rain duration lasting from several minutes to a couple of hours, associated rainfall can be most intense. On the other hand, while tropical cyclones and tropical depressions are near the top of the range with areas commonly in excess of 100 000 sq km and with rainfall duration of several days being common, precipitation is largely from stratiform cloud and is usually of moderate intensity when compared with convective counterparts.

3 Simulated climate

3.1 Seasonality

Whetton and Pittock (1991) argued that poor model simulation of the seasonality of rainfall in the Australian region would represent failure of the model to properly react to regional changes in the annual cycle of radiation, and this would cast doubt on its ability to simulate regional rainfall changes associated with the much smaller radiation changes induced by doubling atmospheric CO_2. They have shown that GCMs do indeed simulate seasonality and that it remains a strong feature for doubled CO_2. Indicative of the simulated change is a 20% increase during the summer months (December, January and February (DJF)) and a similar increase in the winter months (June, July and August (JJA)) over the Northern Territory Top End.

3.2 Rainfall

Experiments with GCMs indicate that total rainfall under enhanced greenhouse conditions may increase by as much as 20% by the year 2030 (and up to 40% by 2070) in the region where summer rainfall predominates (Climate Change 1994). Model simulations reveal a significant increase over the Northern Territory wetlands, although topographic effects (hills, mountains, valleys) and the boundary between land and sea may result in much smaller or larger changes in localised rainfall (Whetton et al 1993).

3.3 Thunderstorms and intensity

Whetton et al (1993) indicate a decrease in the number of raindays but an increase in highest rainfall rates together with a decrease in the lower rates over much of the Australian land mass for winter (JJA) and summer (DJF) for a 2 x CO_2 atmosphere - rainfall intensity was seen to increase even in regions where total rainfall decreases. Increased rainfall intensity (as measured in rain per rain day) under 2 x CO_2 conditions is a feature reported by Gordon et al (1992) who noted that in the southern hemisphere mid-latitudes, the increase in rainfall intensity was more significant and geographically more coherent than changes in total rainfall.

Only in the Australian tropics, including the Northern Territory wetland areas, did model simulations suggest a slight, although not significant, increase in rain day numbers whereas areas of increased rainfall intensity were found to occur over much of the tropical Australian landmass.

Most likely reasons for increased rainfall intensity include a more vigorous monsoon circulation and/or the improved capacity of the warmer atmosphere to hold water vapour.

The concept of a more intense monsoon is supported by Suppiah (1994) who found that simulated patterns of streamlines under 2 x CO_2 conditions indicate a tendency for strengthening the circulation during wet conditions. During wet conditions, an intensified cyclonic circulation near the Pilbara region caused strengthened monsoonal winds to be simulated.

Coincident with increased atmospheric temperature is an improved capacity of the atmosphere to hold water vapour. However, this alone does not increase the potential for more intense rainfall, since the essential ingredient of uplift within the storm is unaffected. It is suggested that thunderstorm development may be self limiting, that is, once the preconditions of moisture and heating are present, a thunderstorm will develop irrespective of how much warmer ambient conditions become; this does not preclude an increase in the number of thunderstorms in a warmer, moister environment. On the other hand, while models are commonly estimating average temperature increases in the range 1.5–4.5°C, which suggests further available heating for thunderstorm development, the spread of the increased temperature between day-time and night-time remains uncertain. A notable feature over considerable areas of the northern hemisphere is that recent warming is primarily due to an increase in night-time temperatures due in part to increases in cloudiness; the direct cooling effect of aerosols on maximum temperature in sunny conditions cannot be excluded (Climate Change 1992).

3.4 Tropical cyclones

It has long been known that tropical cyclone formation and intensification requires, inter alia, a lower limit of 26°C on sea surface temperature (SST). Lighthill et al (unpub) have suggested that 'global warming' will display a strong regional distribution and that tropical ocean temperatures will change the least, with SST increasing by only about 1°C. Increased SSTs does not necessarily imply greater potential for increased numbers of tropical cyclones since there is no observational evidence of a link between tropical cyclone frequency and SST once the lower limit has been surpassed.

Both Lighthill et al (unpub) and Holland (unpub) deduce that there will be insignificant change, above the current natural variability, to the worst possible tropical cyclone resulting from the modest simulated increases in SST associated with anthropogenic climate change. Additionally, using new thermodynamic techniques for the estimation of cyclone maximum potential intensity, Holland (unpub) argues, contrary to previous predictions, that more intense cyclones are unlikely.

3.5 El Nino-southern oscillation

Australia's climate is sensitive to the El Nino-Southern Oscillation (ENSO) phenomenon which influences a number of aspects of Australia's climate including droughts and floods (National Greenhouse Advisory Committee 1992). Tropical cyclone activity in the Australian region is also related to ENSO, with fewer than normal cyclones during El Nino episodes (Nicholls 1994). It also has a modulating effect on the severity and regularity of the monsoon.

At present, climate models cannot properly reproduce ENSO, and El Nino's and anti El Nino's are assumed to continue with the same frequency and duration.

4 References

Annual Report 1994. *Regional Impact of the Enhanced Greenhouse Effect on the Northern Territory - Annual Report 1992–93*. Climate Impact Group, CSIRO Division of Atmospheric Research, 86 pp.

Butterworth I & Arthur J 1993. *Rainfall Trends over the Northern Territory Top End*. Bureau Of Meteorology, Darwin, Research Papers, vol II, 111–116.

Climate Change 1992. *The Supplementary Report to the IPCC Scientific Assessment*. Report Prepared for IPCC by Working Group I, University Press, Cambridge, 200 pp.

Climate Change 1994. *Australia's national report under the United Nations Framework Convention on Climate Change, September 1994*. Department of the Environment, Sport and Territories, AGPS, Canberra, 101 pp.

Gill J 1993. *A Simple Climatology of Severe Wind Gust- Producing Thunderstorms in the Northern Territory*. Bureau of Meteorology, Darwin, Research Papers, vol II, 97–100.

Gordon HB, Whetton PH, Pittock AB, Fowler AM & Haylock MR 1992. *Simulated changes in daily rainfall intensity due to the enhanced greenhouse effect: implications for extreme rainfall events. Climate Dynamics*, 8, 83–102.

Holland G (unpublished). The Maximum Potential Intensity of Tropical Cyclones, Department of Environment, Sport and Tourism.

Lighthill J, Holland G, Gray W, Landsea C, Craig G, Evans J, et al (unpublished). Global Climate Change in Tropical Cyclones, Department of Environment, Sport and Tourism.

Madden RA & Julian PR 1971. *Detection of a 40 to 50 day oscillation in the zonal wind in the tropical Pacific*. Journal of Atmospheric Science 28, 702–708.

McQuade C, Arthur J & Butterworth I (in press). *Climate and Hydrology of the Kakadu Region*. In Finlayson CM and von Oertzen I (eds) *Landscape and Vegetation Ecology of the Kakadu Region Northern Australia,* Kluwer Academic Publishers, Dordrecht.

National Greenhouse Advisory Committee 1992. *Grappling with Greenhouse*. Department of the Arts, Sport, the Environment and Territories, Commonwealth of Australia.

Nicholls N 1994. SOI-based Forecast of Australian Region Tropical Cyclone Activity. In *Experimental Long-Lead Forecast Bulletin*, NOAA vol 3, No 4, 16–17.

Suppiah R 1994. *Synoptic aspects of wet and dry conditions in central Australia: observations and GCM simulations for 1 x CO_2 and 2 x CO_2 conditions. Climate Dynamics*, 10, 395–405.

Taylor JA & Tulloch D 1985. *Rainfall in the wet-dry tropics: Extreme events at Darwin and similarities between years during the period 1870–1983 inclusive. Australian Journal of Ecology* 10, 281–295.

Whetton P & Pittock AB 1991. *Australian Region Intercomparison of the results of some General Circulation Models used in Enhanced Greenhouse Experiments*. CSIRO Division of Atmospheric Research Technical Paper No 21, 73 pp.

Whetton PH, Fowler AM, Haylock MR & Pittock AB 1993. *Implications of Climate Change due to the Enhanced Greenhouse Effect on Floods and Droughts in Australia*. Climate Change 25, 289–317.

ASSESSING THE VULNERABILITY OF THE COASTLINES OF THE WET-DRY TROPICS TO NATURAL AND HUMAN INDUCED CHANGES

P WATERMAN RFD

Research Director, Environmental Management Services Pty Ltd,
40 Dixon Drive, Holder, ACT 2611

ABSTRACT

Coastlines of the wet-dry tropics are vulnerable to two sets of factors. The first are the natural factors which include diurnal and seasonal tidal oscillations, tropical cyclones and storm surge events. When combined, theses factors can result in increased shoreline erosion flooding and mobilisation of sediments in estuarine and catchment areas. The second set of factors are anthropogenic and at one level include the massive clearance and/or filling of wetlands to accommodate port, industrial and recreational developments. At the other end of the spectrum anthropogenic factors include the insidious provision of access along sensitive beaches and penetration into swamps and mangrove habitats for recreational and commercial pursuits. Assessment of the vulnerability of the wet-dry tropical coastlines must take into account both sets of factors. When undertaking vulnerability assessments, all of the factors need to be considered in the context of: the natural resilience of the wet tropic coastal wetland systems to recover from natural catastrophic events; the possible effects on the cultural values of the coastal zone in terms of Aboriginal and natural heritage; and the social and economic costs of siting facilities and developments within zones that may be subject to natural hazards.

Keywords: anthropogenic factors, forcing factors, primary impacts, responses, natural hazards, storm surge, tidal oscillations, resilience, sea level rise, vulnerability assessment.

1 Introduction

Through the Department of Environment, Sport and Territories (DEST), the Australian government has embarked on a project involving all the states and the Northern Territory (NT), which aims at developing an approach (or approaches), sharing common features, for assessing the vulnerability of the coastal zone to natural and human induced change. One of the objectives of the project to integrate 'vulnerability assessment' (VA) into the coastal management processes of the states and the NT (Kay & Waterman 1993). Integration will be achieved within the framework of existing state/territory policy initiatives and directives as well as the administration arrangements for coordinating planning and natural resource/environmental management in the coastal zone.

1.1 Why Carry Out Vulnerability Assessments?

The integration of VA into the coastal management processes for coastal Australia is necessary at a range of geographic and governmental scales in order to:

- establish common standards to enable governments (national, state, local, community council) to respond to the impacts of natural and human induced changes in the coastal zone

- assess the liability arising from previous land use planning decisions in coastal areas which were taken before the implications of the potential environmental impacts of the full range of natural and human induced changes were appreciated
- formulate plans (strategic, statutory, action) to cover contingencies arising from the impacts of extreme climatic events as well as other environmental effects arising from natural changes and human activities
- support decisions intended to prevent and/or mitigate impacts arising from climatic and human induced changes
- provide bench-marks against which to monitor the success of decisions intended to prevent and/or mitigate impacts arising from natural and human induced changes.

1.2 The Context

Development of a 'common approach' and the integration of VA into coastal zone management is being undertaken as one of the Commonwealth Government's international responsibilities in responding to concerns as to the possible impact of climate change on the coastal zone. In this context, the VA project is part of Australia's contribution to work initiated by the Intergovernmental Panel on Climate Change (IPCC).

2 The Approach

The IPCC developed a Common Methodology (IPCC 1991) for VA which was tested on mainland Australia (Kay et al 1992, Morvell 1993), the Cocos Islands (Woodroffe & McLean 1993, McLean & Woodroffe 1993) and by a wide range of other nations (IPCC 1994). The Common Methodology, which was strongly cost-benefit analysis and engineering orientated, was found to be deficient (McLean & Mimura 1993, IPCC 1994). The case studies being carried out in Australia are an essential step in rectifying the deficiencies with the IPCC 'Common Methodology' reported at the IPCC Eastern Hemisphere Workshop (McLean & Mimura 1993) and the IPCC World Coast Conference 1993 (IPCC 1994). The term 'Common Methodology' is no longer used when considering the approach to VA.

The common approach(es) being developed in Australia seeks to accommodate regional and local differences in coastal regimes by way of physical, biological and geographic and economic conditions, as well as the social and cultural variations, within and across the governmental jurisdictions of the Australian federal system. Further, the approach seeks to build upon the policy frameworks and the strengths of the coastal management processes and procedures in terms of the institutional and administrative arrangements of the states and the Northern Territory.

The common approach(es) will seek to address the vulnerability of coastal areas to both natural and human (anthropogenic) induced changes. Covering both sets of factors is essential if the long term impacts of climate induced change are to be determined, planned for, and managed. By addressing both natural and human induced changes the VA will have immediate utility as it will assist in putting the natural variability of coastal systems (climatic, oceanographic, geomorphic, hydrological, ecological) and the resilience of the systems into planning and management frameworks which allow responses to be developed, costed and implemented in ways which are endorsed politically and understood by the broader community. This will be done by utilising available information, initiating studies to fill the information deficiencies, using appropriate spatial information management tools and decision support systems. Additionally, it will build on and develop innovative approaches for governmental and community involvement in coastal zone management.

3 The Case Studies

Two VA case studies will be undertaken for the wet-dry tropics. One assessment will be directed by the Northern Territory Department of Lands and Housing and will cover the coastal zone of the Darwin planning region. The second study will be directed by the Environmental Research Institute of the Supervising Scientist (***eriss***) and will broadly cover the coastal zone of the Alligator Rivers Region from the Mary River wetlands to the west across the Kakadu National Park to the East Alligator River.

The case study areas are in the one biophysical region. Each area exhibits distinctive subregional characteristics which make them biophysically different. The Darwin region is characterised by drowned river valleys (rias) with major stands of mangroves. In contrast, the Alligator Rivers Region is a major wetland with a mangrove fringed shoreline of low elevation facing onto the van Diemans Gulf. These wetlands have already been identified as being vulnerable to climatic and other changes (Woodroffe et al 1986, Woodroffe & Mulrennen 1993) and may not be resilient.

3.1 Why the Wet Tropics?

Although neither highly populated nor under the types of human pressures of the metropolitan and recreational coastlines south of the Tropic of Capricorn, the coastal zones of the wet tropics are vulnerable to both natural and human changes. As the least populated the natural systems are less researched and understood. In particular, the resilience of shorelines and wetland ecosystems following catastrophic events.

In the absence of information on the vulnerability of the coastal zone to natural exchanges facilities and developments have been (and could continue to be) sited in zones prone to the effects of natural hazards (storm surge, flooding). To continue to develop in hazard zones could have, in the future, unwanted social consequences and economic costs.

Additionally, the cultural values of coastal areas of the wet-dry tropics are of particular importance. For the Aboriginal people cultural interest encompasses both the traditional use of these areas for hunting and gathering as well as the spiritual significance of the coastal lands and waters. Cultural interest also extends to the natural values of wet-tropic coastlines, estuaries, and wetlands from Cape York to south of Broome. This wet-tropical coastal zone is physically and ecologically diverse. As well, the zone displays a diverse range of scenic character ranging from white sands of Cable Beach at Broome, the drowned river valleys of the Kimberley coastline to the mangrove lined shores and vast grass covered wetlands of the Alligator River region, to the coastal lagoons and mudflats of the Gulf of Carpentaria.

3.2 Approach to the VA Case Studies

The approach to be followed for the two case studies should be collegiate, holistic and integrative. Both areas share common issues and problems and by having the same Steering Committee will develop a clear inter and intra-governmental focus. With a collegiate approach all stakeholders can be readily involved (governmental and communities of interest). The studies will be holistic in that they will cover physical, biological, social, economic and cultural and the results will be applicable at a range of geographic scales. The assessments will be integrative in that they will bring together the key professional, governmental elements involved in the management process and join them with the scientific and technological expertise needed to resolve the issues relating to the impacts of natural and human induced change. As such, a 'change management' team will be developed which will integrate the policy, planning, engineering and scientific requirements necessary to resolve the issues identified.

4 Framework and Factors

A suggested framework for the assessments of the vulnerability of the coastal zone of the wet-dry tropics to natural and human induced changes is given in figure 1. This figure shows that the natural and anthropogenic (human) forcing factors have effects on a range of environmental attributes. These attributes cause a range of primary impacts which have affects on the natural systems as well as the social, economic and cultural systems which in turn affect governmental systems. From the governmental systems there may emanate a range of responses and actions which can impinge upon the forcing factors.

The affects on the three systems are most important and collectively they cover a wide range of issues. Table 1 lists the issues that will need to be considered. For the VA they will be addressed using existing information and utilise tools such as a geographic information system (GIS) to hold and analyse spatial and descriptive data and information. Some information may not be available or too expensive to collect. The process of reviewing the issues and determining their relevant importance is a key component of the assessment process. The product of the process will be maps and a report indicating the vulnerability, the resilience and the institutional and community responses needed in the short, medium and long terms.

5 Concluding Remarks

The case studies for the wet-dry tropics will make an important contribution to the development of a common approach to integrating VA into the coastal management processes of the states and the NT. By sharing a Steering Committee, information sources and technical expertise, the two studies will demonstrate that they have achieved a level of commonality in being collegiate, holistic and integrative. By working together to address problems common to both case study areas there will be an opportunity to develop skills in the assessment of hazards and risks in the coastal zone. Whilst working on the issues particular to the case study locations there will be an opportunity to share experiences. Overall, the process of issue scoping and resolution assists in enhancing professional capability in the field of coastal management.

6 Acknowledgments

Work on vulnerability assessment is being funded through the Marine and Coastal Group, Climate Change and Marine Branch, of the Department of Environment, Sport and Territories. The roles played by Gerry Morvell and Mark Flanigan in initiating this project is pivotal to the success of this intergovernmental initiative. The author is also grateful for the advice provided for this paper by Dr Ian Eliot, Department of Geography, University of Western Australia. The assistance of Adrianne Waterman with the preparation of this paper is gratefully acknowledged.

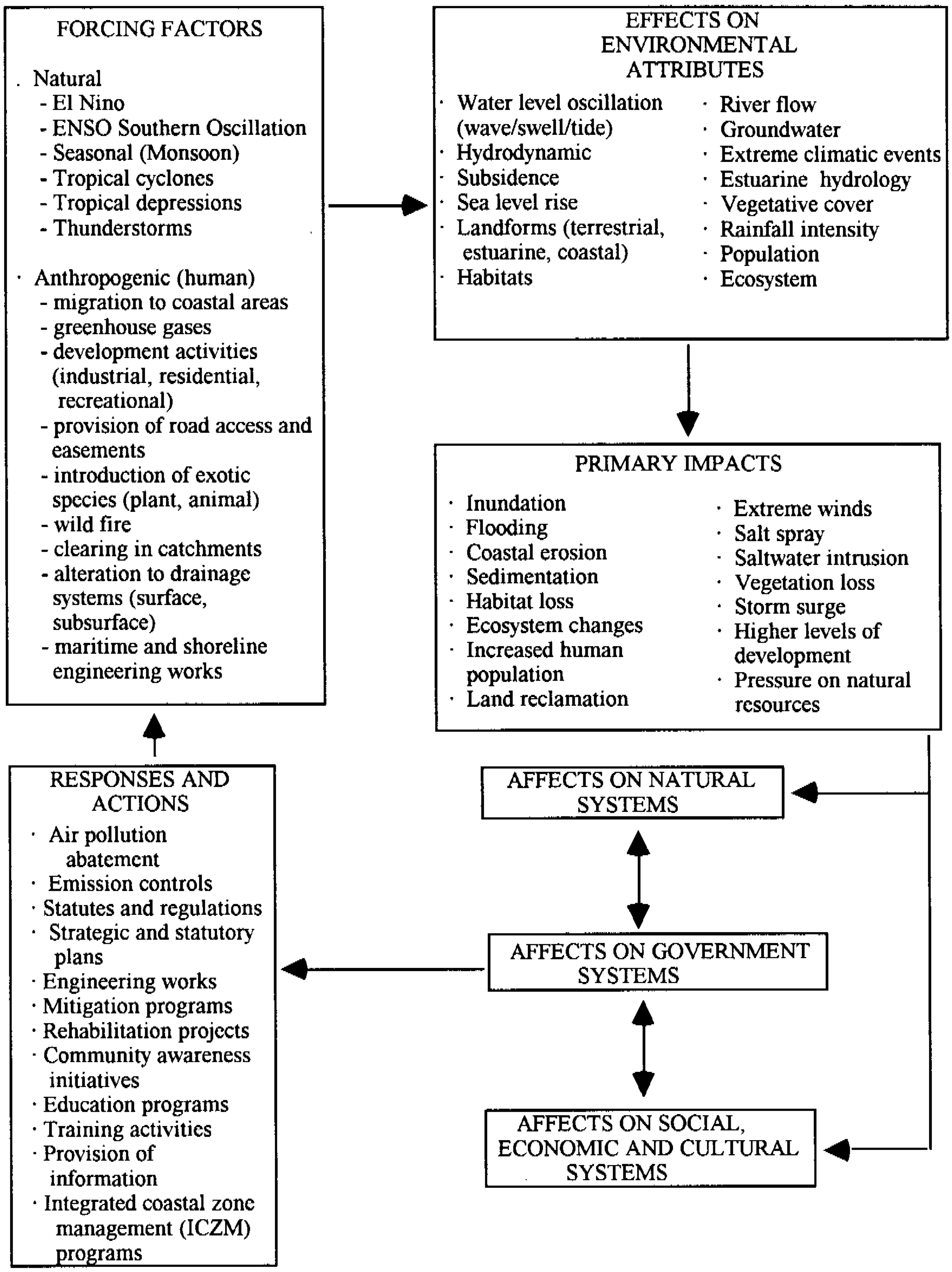

Figure 1 Suggested framework for the assessment of coastal vulnerability

1 Natural Systems

Table 1 Issues to be considered in the vulnerability assessment methodology for determination of the potential impacts of climatic and other changes on the coastal zone

1.1 Change in Climate Conditions	1.1.1 Storm frequency and intensity 1.1.2 Extreme wind events 1.1.3 Cyclone events 1.1.4 Intense tropical lows 1.1.5 Seasonal changes in temperature 1.1.6 Seasonal changes in precipitation 1.1.7 Seasonal changes in evaporation 1.1.8 Changes in the monsoonal regime
1.2 Change in Wave Climate	1.2.1 Modal annual wave height 1.2.2 Modal wave direction 1.2.3 Change in annual wave energy
1.3 Change in Hydrological Conditions	1.3.1 Ten year peak river discharge 1.3.2 Groundwater discharges 1.3.3 Water table fluctuation 1.3.4 Salinisation (salt intrusion) 1.3.5 Flood hazards 1.3.6 Riverine and estuarine morphology (channel erosion, deposition and mobilisation of sediments)
1.4 Change in Water Level Oscillation	1.4.1 Tidal condition 1.4.2 Storm surge events 1.4.3 Nearshore circulation patterns 1.4.4 Estuarine water circulation
1.5 Changing Shoreline Conditions	1.5.1 Bay shape 1.5.2 Shoreline planform 1.5.3 Beach gradients 1.5.4 Sediment budget 1.5.5 Historic stratigraphic records (Chernier development)
1.6 Changing Biological Conditions	1.6.1 Stability of nearshore marine habitats 1.6.2 Stability of coastal and estuarine wetland habitats 1.6.3 Rare and endangered species 1.6.4 Habitat adjustment (historic change in climate) 1.6.5 Invasion by exotic species (plant, animal) 1.6.6 Effects of wild fire

2 Cultural, Social and Economic Systems

2.1 Cultural and Heritage Conditions	2.1.1 Values of traditional owners (spiritual, cultural, economic) 2.1.2 European cultural values 2.1.3 Moveable heritage items 2.1.4 Natural heritage areas 2.1.5 Sites of scientific and related interest
2.2 Social Conditions	2.2.1 Land tenure and land use 2.2.2 Demographic structure 2.2.3 Housing ownership 2.2.4 Employment levels 2.2.5 Educational levels 2.2.6 Internal migration levels
2.3 Economic Conditions	2.3.1 Household incomes 2.3.2 Disposable income 2.3.3 Workforce structure 2.3.4 Evaluation of local investment 2.3.5 Environmental economic values 2.3.6 Actuarial (insurance responsibilities)
2.4 Tourist and Recreation Conditions	2.4.1 Provision of access (land, air and water) 2.4.2 Tourist destinations 2.4.3 Recreation destinations 2.4.4 Tourist/recreation facilities 2.4.5 Ecotourism attractions (natural, cultural, scientific)
2.5 Community Infrastructure	2.5.1 Public recreational areas 2.5.2 Power/energy services 2.5.3 Sewage and water services 2.5.4 Transportation services (land, air, water) 2.5.5 Governmental facilities 2.5.6 Port facilities 2.5.7 Airport facilities 2.5.8 Public access easements
2.6 Private Infrastructure	2.6.1 Industrial/business/commercial areas 2.6.2 Residential areas 2.6.3 Canal estates/marinas 2.6.4 Private access easements 2.6.5 Tourist/recreational attractions

3 Governmental Systems

3.1 Commonwealth Considerations	3.1.1	International obligations
	3.1.2	Policy frameworks
	3.1.3	Legislative frameworks
	3.1.4	Cultural/heritage considerations
	3.1.5	Decision making networks
	3.1.6	Education and training provisions
	3.1.7	Community awareness
	3.1.8	Intergovernmental liaison and co-ordination
3.2 State/Territory Considerations	3.2.1	Policy frameworks
	3.2.2	Legislative and regulatory frameworks
	3.2.3	Engineering responses
	3.2.4	Planning implications
	3.2.5	Decision making networks
	3.2.6	Education and training
	3.2.7	Community awareness
	3.2.8	Intergovernmental liaison and co-ordination
3.3 Local Government Considerations	3.3.1	Strategic and statutory planning frameworks
	3.3.2	Land use and development control implications
	3.3.3	By-Laws/regulations
	3.3.4	Coastal management programs and prescriptions
	3.3.5	Mitigation measures
	3.3.6	Community awareness
	3.3.7	Risk analysis and risk sharing
	3.3.8	Intergovernmental liaison
	3.3.9	Supporting community initiatives (land care, coast care)
	3.3.10	Participative consultations
	3.3.11	Duty of care and due diligence
3.4 Community Considerations	3.4.1	Community based projects (Landcare/Coast Care/Greening Australia etc)
	3.4.2	Integrated catchment management projects
	3.4.3	Community awareness projects
	3.4.4	Educational projects
	3.4.5	Participative consultations

7 References

IPCC 1991. *Common Methodology for Assessing Vulnerability to Sea-level Rise.* Ministry of Transport and Public Works, The Netherlands, The Hague.

IPCC 1994. *Preparing to Meet the Challenges of the 21st Century.* Conference Report. World Coast Conference, 1993, Noordwijk, The Netherlands. 1–5 November 1993.

Kay R, Eliot I & Klem G 1992. *Analysis of the IPCC Sea-Level Rise Vulnerability Assessment Methodology using Geographe Bay, SW Western Australia as a Case Study.* Report to DASET, Canberra.

Kay R & Waterman P 1993. Review of the Applicability of the 'Common Methodology for Assessment of the Vulnerability to Sea-Level Rise' to the Australian Coastal Zone. In McLean R & Mimura N (eds) *Vulnerability Assessment to Sea-Level Rise and Coastal Zone Management.* Proceedings IPCC Eastern Hemisphere Workshop, Tsukuba, Japan. 3 – 6 August 1993, 237–48.

McLean R & Mimura N (eds) 1993. *Vulnerability Assessment to Sea-Level Rise and Coastal Zone Management.* Proceedings IPCC Eastern Hemisphere Workshop, Tsukuba, Japan. 3–6 August 1993.

McLean RF & Woodroffe CD 1993. Vulnerability of Atolls to Accelerated Sea-Level Rise: A Case Study of Australia's Cocos (Keeling) Islands. In McLean R & Mimura N (eds) 1993. *Vulnerability Assessment to Sea-Level Rise and Coastal Zone Management.* Proceedings IPCC Eastern Hemisphere Workshop, Tsukuba, Japan. 3–6 August 1993.

Morvell GL 1993. *The Application of the IPCC Common Methodology for Assessment of Vulnerability to Sea-Level Rise in Australia and its Territories.* Key Note Speech. World Coast Conference, 1993. Noordwijk, The Netherlands. 1–5 November 1993.

Woodroffe CD, Chappell JMA, Thom BG & Wallensky E 1986. *Geomorphological Dynamics and Evolution of the South Alligator Tidal River and Plains, Northern Territory.* Australian National University, North Australia Research Unit. Mangrove Monograph No. 3, Darwin.

Woodroffe CD & Mulrennen ME 1993. *Geomorphology of the Lower Mary River Plains, Northern Territory.* Australian National University, North Australian Research Unit, Conservation Commission of the Northern Territory, Darwin.

Woodroffe CD & McLean, RF 1993. *Cocos (Keeling) Islands: Vulnerability to Sea-Level Rise.* Climate Change and Environmental Liaison Branch, Department of Environment, Sports, Territories, Commonwealth Government of Australia, Canberra.