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Tropical wetlands: Information for environmental training, management and research

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supervising scientist

Tropical wetlands: Information for environmental training, management and research

Information base compiled for a training unit in Tropical Wetland Management conducted by *eriss* on behalf of the Northern Territory University

Jabiru, Australia

Edited by

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Environmental Research Institute of the Supervising Scientist

Internal Report

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Foreword

In 1997 ***eriss*** presented a formal training module on the management and protection of tropical wetlands. This was done in collaboration with the Northern Territory University as a component of their Masters in Tropical Environmental Management. The module covered a two week period and encompassed formal lectures, slide and video presentations, computer demonstrations, laboratory and field exercises, discussion sessions and student projects. Presentations were made by many ***eriss*** staff and invited lecturers from an array of agencies/institutions: Northern Land Council; Parks Australia North; Northern Territory Department of Lands, Planning and the Environment; Department of Law, University of Wollongong; Remote Area Training Unit, Northern Territory University; Gagudju Association; and the Lower Mary River Landcare Group. This made for a very diverse and thought-provoking course.

Throughout the module a large amount of information was presented by the scientific professional and technical staff from ***eriss*** and invited lecturers. This report is a compendium of much of that information. As such it represents an important information resource for wetland training, management and research in tropical Australia. The information is specifically directed towards wetlands of the Australian Wet-Dry tropics but, given the similarities between wetlands of northern Australia and those elsewhere in the tropical regions of the world it also represents a valuable resource for a much broader audience.

The information in the report is presented as a series of formal scientific papers along with transcripts of less formal presentations. The formal and informal papers are interspersed within broad thematic headings. This combination adds a further dimension to the compendium with a variety of material of interest to wetland managers, owners, users and researchers being presented.

The production of this compendium marks the culmination of an extensive effort by many people—the lecturers and authors, laboratory and field assistants, administrative and logistical support staff. We are grateful for their support. We are also grateful for the interaction with and feedback from the students. Thank you to the many people who contributed.

Max Finlayson & Abbie Spiers

Tropical Wetlands: Information for environmental training, management and research

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Information needs for wetland management

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Abstract

Wetland management is today receiving far greater attention within the framework of both general and specific conservation policies. Many jurisdictions have realised the full value of their wetland resources and have begun to implement specific management activities. For these activities they require further information to ensure the resources are managed and used in a wise manner. Information on the current status of wetlands, the extent of wetland loss and degradation, conservation procedures and the success of monitoring strategies is required. This information can be collected through ongoing wetland inventory (incorporating classification) and monitoring programs. Wetland managers in northern Australia can draw upon an increasing amount of information from other regions of the world, but they will still need an interactive inventory process to provide locally relevant information. Management actions also require monitoring to ensure their effectiveness. In turn, monitoring requires the support of management procedures to ensure it is effective and that the outcomes are interpreted and acted upon. A management plan can provide such procedures and ensure that the available information is presented in a form that can be readily used for management actions.

Keywords: wetlands, northern Australia, inventory, monitoring, management planning

1 Introduction

Over the last decade considerable effort has been directed towards the conservation and wise use of wetlands in northern Australia (Jonauskas 1996, Finlayson et al 1997, Fleming 1993, Blackman et al 1993, 1995). However, despite having compiled a general level of knowledge the information base is not even. Whilst reasonable data/information exists for some wetlands and/or threats to wetlands, a comprehensive inventory at the most basic level (encompassing, for example, information on physical and ecological features, values and benefits, land tenure and uses, threats and disturbances, and monitoring and restoration) of all wetlands across this vast region is not available (Storrs & Finlayson 1997, Finlayson et al 1997).

The wise use and conservation of wetlands in northern Australia will be partly reliant on a greatly expanded information base. Information on the ecological character of wetlands, the extent of wetland loss and degradation, conservation procedures and the success of monitoring strategies will be required. In turn, this information base requires linkage and integration with managerial processes – a management planning procedure provides this.

Integral to obtaining this information is the application of the basic, but often controversial process (see Finlayson & van der Valk 1995) of classifying wetlands. Classification and inventory of wetlands are processes designed to provide a summary of knowledge on wetlands and their resources. A review of the basic concepts of wetland classification and inventory is presented along with a summary of the concept of ecological character of a wetland (Dugan &

Jones 1993, Finlayson 1996a) and the importance and role of monitoring (Tomas Vives 1996) and management plans (Davis 1994) for the wise use of wetlands. Management plans are presented in the role of processes that integrate management actions and monitoring to ensure that the ecological character of the wetland concerned is maintained whilst being used for specified values and benefits to society.

2 Definition of wetlands

The term 'wetland' groups together a wide range of habitats that share a number of common features, the most important of which is continuous, seasonal or periodic standing water or saturated soils. Despite a number of national/regional wetland surveys (see McComb & Lake 1988, Finlayson & von Oertzen 1993) there is no standard definition of wetlands in Australia (Barson & Williams 1991, Pressey & Adam 1995). The recent *Directory of Important Wetlands in Australia* (Usback & James 1993, ANCA 1996) uses the Ramsar International Wetland Convention definition of a wetland

> '...... *wetlands are areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.*'

Paijmans et al (1985) undertook a national overview of wetlands and used the following definition

> '... *land permanently or temporarily under water or waterlogged. Temporary wetlands must have surface water or waterlogging of sufficient frequency and/or duration to affect the biota. Thus the occurrence, at least sometimes, of hydrophytic vegetation or use by waterbirds are necessary attributes.*'

LWRRDC in a national review of wetland research and development needs (Bunn et al 1997) adopted the Paijmans et al (1985) definition. Thus, when considering wetland classification and inventory it is important to ascertain the breadth of 'wetland' habitat that will be covered (ie determine what definition is being used). In northern Australia the broad-based Ramsar definition is being increasingly used (Finlayson 1995, Storrs & Finlayson 1997).

3 Ecological character

An important obligation under the Ramsar International Wetland Convention is for each Contracting Party to '*designate suitable wetlands within their territory for inclusion in a List of Wetlands of International Importance*'. The Convention also states that wetlands should be Listed according to their '*international significance in terms of ecology, botany, zoology, limnology or hydrology*'. Whilst listing a site as internationally important is an important obligation under the Convention it may not constitute anything more than a passive conservation step. Thus, the Convention also contains an obligation to '*....formulate and implement their planning so as to promote the conservation of the wetlands included in the List.*' and to inform the Ramsar Bureau '*.....if the ecological character of any wetland in their territory and included in the List has changed, is changing, or is likely to change as the result of technological developments, pollution or other human interference*'. Thus, under this Convention there is an obligation to maintain (or restore) the ecological character of Listed sites (and, in fact, of all wetlands).

In 1992 the International Waterfowl and Wetland Research Bureau (IWRB) discussed the concept of ecological character and accepted a working definition that was proffered by Dugan and Jones (1993). The Ramsar Convention Scientific and Technical Review Panel (STRP) refined the definition (Finlayson 1996a) and this is presented below

> *'The ecological character of a wetland is the sum of the wetland's functions, products, and attributes that are derived from the individual biological, chemical, and physical components of the ecosystem and their interactions.'*

This wording reflected an international consensus and was presented as a working definition that could be changed following further discussion. This in fact occurred at the next conference of the Wetland Convention in 1996 and the following working definition was adopted

> *'The ecological character is the structure and inter-relationships between the biological, chemical, and physical components of the wetland. These derive from the interactions of individual processes, functions, attributes and values of the ecosystem(s).'*

The main difference between the definitions is that the first deliberately includes wetland values and benefits (functions, products and attributes) in addition to biophysical features. Thus, the ecological character of a wetland is, in part, defined by the uses made of it by people. In the second instance the direct reference to wetland values has been removed, although it is acknowledged that the use of the wetland can affect the ecological character. This change was made as there was unease at the direct linking of ecological and socio-economic concepts. It is noted, however, that the latter is also presented as a working definition and it could be changed.

Both definitions refers to wetland functions, products and attributes (values and benefits). These terms have been previously described within the Ramsar context (Dugan 1990, Davis 1993, 1994) and are presented below

Functions performed by wetlands include the following: water storage; storm protection and flood mitigation; shoreline stabilisation and erosion control; groundwater recharge; groundwater discharge; retention of nutrients, sediments and pollutants; and stabilisation of local climatic conditions, particularly rainfall and temperature. These functions are the result of the interactions between the biological, chemical and physical components of a wetland, such as soils, water, plants and animals.
Products generated by wetlands include the following: wildlife resources; fisheries; forest resources; forage resources; agricultural resources; and water supply. These products are generated by the interactions between the biological, chemical and physical components of a wetland.
Attributes of a wetland include the following: biological diversity; geomorphic features; and unique cultural and heritage features. These have value either because they induce certain uses or because they are valued themselves.

The combination of wetland functions, products and attributes give the wetland *benefits and values* that make it important to society.

The above terms provide a theoretical basis for describing the ecological character of a wetland, but do not assist with the practical issues of describing the character – what is an adequate level of baseline description and can this be used as a basis for assessing the significance of any change? Thus, there is a level of consensus (but not agreement) on the key concept (ie definitions) of ecological character, but the harder questions relating to the ecological meaning of change when it is detected have yet to be agreed. Monitoring can provide the necessary information, but it does not necessarily provide the basis for interpreting the significance of change.

Within the context of the International Wetland Convention change in ecological character was considered as meaning adverse change. (It was noted that positive change could occur and that this was already covered by the management planning and restoration guidelines developed by the Ramsar Convention.) This concept is captured in the definition of change in ecological character proposed by Dugan & Jones (1993) and slightly modified by STRP (Finlayson 1996a)

> *'Change in ecological character of a wetland occurs as the result of technological developments, pollution, or other human interferences with the biological, chemical, and/or physical components of the ecosystem (and/or the interactions between them), to such an extent that a reduction and/or an ongoing imbalance occurs in any of those functions, products and attributes which give the wetland benefits and value to society'.*

However, even with this definition we are no closer to ascertaining what exactly constitutes an unacceptable ecological change. To define an unacceptable ecological change we need to firstly establish the values and benefits of the wetland, assess the ecological status of these and then monitor them to ascertain when (if) an adverse change is likely to or has actually occurred. At a superficial level this may seem a straight forward exercise, but in reality, all three steps are bedevilled by technical and/or socio-economic difficulties that can undermine the management, including monitoring, and wise use and conservation of wetlands (Hollis et al 1992, Finlayson 1994, 1996b, Hollis & Finlayson 1996).

The same comments apply to the definition of change in ecological character adopted by the Convention in 1996

> *'Change in the ecological character of a wetland is the impairment or imbalance in any of those processes and functions which maintain the wetland and its products, attributes and values.'*

Thus, there is broad agreement on the basic need to assess and describe the ecological character of a wetland, but further attention is required to assessing the significance of any change. For the latter to occur, further attention to inventory (that provides the basic description of the wetland) and monitoring (that describes the extent of any change) is required.

4 Wetland classification

The classification of wetlands is beset with difficulties (Finlayson & van der Valk 1995) and these seemingly multiply when a regional or an international approach is sought (Scott & Jones 1995). The purpose of wetland classification is to standardise and define the terms being used to describe the various wetland types. At an international level a uniform set of terms is needed (Cowardin & Golet 1995, Scott & Jones 1995, Zoltai & Vitt 1995). Pressey & Adam (1995) argue that at a local or national level this may not be necessary, although there would seem to be little argument that the adoption of standardised terms and definitions has definite advantages for comparative and broad planning purposes (Cowardin & Golet 1995, Hughes 1995, Zoltai & Vitt 1995).

Scott & Jones (1995) issued a warning concerning the level of sophistication required for classification in relation to the amount of information required for management. Careful consideration of the need for information and the requirements for management purposes are points strongly made by Pressey & Adam (1995). The important point in classifying wetlands is not the detail of the classification, but the usefulness of the classification for management purposes.

Many national wetland classifications now exist (see Cowardin & Golet 1995, Lu 1995, Pressey & Adam 1995, Semeniuk & Semeniuk 1995, Zoltai & Vitt 1995). These invariably incorporate local terms and definitions that are not necessarily known or accepted elsewhere. For national purposes this may not be a major problem, but for comparisons and management at an international level these differences may present difficulties. However, even at the national level it can be extremely difficult to develop a classification that is acceptable to all wetland scientists and experts (Cowardin & Golet 1995, Lu 1995, Pressey & Adam 1995).

An overview of the classification of northern Australian wetlands has been provided by Finlayson & von Oertzen (1993). They list four completely different approaches (table 1) and can now be complemented by two further systems (Semeniuk 1987, Semeniuk & Semeniuk 1995, 1997, ANCA 1996). The inconsistencies within classifications similar to that adopted by the Ramsar Wetland Convention (such as that used by ANCA 1996) have been pointed out by Semeniuk & Semeniuk (1995, 1997).

Inconsistencies identified in wetland classifications
• not all types of wetlands are clearly or unambiguously described
• repetition of types that are named 'marshes'
• some wetlands remain ill-defined and encompass a number of types
• mixed criteria are used to separate wetlands

In order to overcome such inconsistencies Semeniuk & Semeniuk (1995, 1997) propose a geomorphic approach to wetland classification based on landform setting and hydroperiod. It is systematic with a hierarchical use of descriptors added to core wetland types.

5 Wetland inventory

The information collected through wetland inventories is nowadays regarded as a necessary prerequisite for wetland conservation and management at a holistic level, involving planning on a national, regional and international scale (Dugan 1990, Hollis et al 1992, Taylor et al 1995, Hughes 1995, Naranjo 1995, Scott & Jones 1995). An inventory is regarded by Dugan (1990) as the first step in assembling an information base for wetland management. In fact, Contracting Parties to the Ramsar Convention undertake to compile an inventory as part of the process of developing and implementing a national wetland policy for the wise use of all wetlands on their territory. Strategically developed wetland inventory (or inventories) should provide managers and/or policy makers with the information base that they require not only to manage individual wetlands or threats, but to also place the conservation value of wetlands within the context of broadscale (catchment, regional or even national) land use and sustainable development priorities.

To be effective in promoting the conservation of wetlands these inventories must be available to and understood by all those formulating and implementing wetland management policies (Naranjo 1995, Pressey & Adam 1995, Wilen & Bates 1995). Thus, they must be framed in a manner suitable for management purposes. Additionally, to remain useful tools for management they need to be regularly reviewed and updated (Naranjo 1995, Scott & Jones 1995, Wilen & Bates 1995). Information categories often used in wetland inventories are shown in table 2. Many of the categories do not relate directly to biophysical information, but are management oriented.

Inventories are useful in the first stages of developing effective wetland conservation programs (Taylor et al 1995, Hughes 1995, Naranjo 1995, Scott & Jones 1995, Wilen & Bates 1995). They can assist in the identification of conservation priorities, establish the basis for monitoring the ecological status of wetlands, promote awareness of wetland sites and management issues, and facilitate exchange of information and comparisons between sites and regions. As importantly, information gathered for inventories can also illustrate the economic value of wetlands and provide valuable data for resource utilisation decisions.

Inventories are particularly valuable for assessing wetland loss and degradation (Taylor et al 1995, Hughes 1995, Lu 1995, Wilen & Bates 1995). Information on rates of wetland loss and reasons for this loss have proved invaluable for promoting awareness and developing conservation and restoration programs (Hollis & Jones 1991, Hughes 1995, Wilen & Bates 1995). Once the basic information on wetland occurrence, distribution and status has been collated it is essential that it is utilised as the basis of further conservation effort before it becomes dated and not seriously regarded by conservation officials (Naranjo 1995). However, even when inventories are available they may only be of limited use (Hughes 1995, Naranjo 1995). This is particularly so where the information is not comprehensive or is restricted in scope and coverage, or is not brought to the attention of governmental officials responsible for setting policies that affect wetlands.

It is not possible, based on current inventory information, to accurately depict the extent of wetlands across all of northern Australia. A broadscale inventory is lacking, although much information has been collated in the national wetland directory (ANCA 1996). The existence of datasets on wetlands in the Northern Territory was identified by Storrs & Finlayson (1997), but an inventory does not exist. Similarly, in northern Western Australia there has been a recent attempt to collate existing information on major wetlands (Watkins et al 1997), but not a comprehensive inventory. There is much more information on northern Queensland wetlands and this is becoming available (Blackman et al 1993, 1995)

Without a complete inventory of wetlands, management for conservation and sustainable utilisation of wetlands will, in part, continue to be underpinned by an *ad hoc* information base. This is an unsatisfactory situation given the status of wetlands in northern Australia and the value now being placed on them (Finlayson et al 1997, Storrs & Finlayson 1997).

Costa et al (1996) summarised the conclusions of a Mediterranean analysis of wetland inventory. The key points from this summary are given below as a guide to compiling a wetland inventory. Additionally, Costa et al (1996) point out that the undertaking of an inventory allows the development of networks of experts concerned with wetlands, the stimulation of cooperation for undertaking conservation actions, and the promotion of awareness of wetland values and benefits.

Objectives of a wetland inventory
• to identify where wetlands are, and which are priority sites for conservation
• to identify the functions and values of each wetland
• to establish a baseline for measuring change in a wetland
• to provide a tool for planning and management

In order to achieve these objectives the following recommendations were made.

Recommendations to achieve the objectives of an inventory
• use standardised methods for classification, data collection and storage, delineation and mapping • incorporate qualitative and quantitative data to provide a baseline for monitoring wetland change and loss • facilitate analysis of loss of wetland functions • be regularly updated • be easily disseminated and made available to wetland managers, decision-makers and the general public.

For the above to be achieved careful planning and testing of techniques is required. A secure funding source is needed and all changes to protocols should be well documented and assessed. Critically, any limitations on the use of the information should be made apparent at the outset.

6 .Monitoring

Environmental monitoring has received more and more attention in recent years. At a global level this has arisen as awareness of the extent of environmental degradation and habitat loss has increased. Wetlands have not been exempt from this general and widescale degradation (see, for example, cases described in Finlayson et al 1992). Such is the concern at the extent of global wetland degradation that more and more effort is being directed towards developing effective management processes and responses to problems. In many instances this effort is being held back by a lack of relevant information on the nature of the problem, the cause of the problem and the effectiveness of management procedures and actions. Effective monitoring programs can help overcome these deficiencies.

In a general sense monitoring addresses the issue of change or lack of change through time and at particular places. Thus **monitoring** can be defined as *the systematic collection of data or information over time*. It differs from **surveillance** by assuming that there is a specific reason for collecting the data or information (see Spellerberg 1991, Hellawell 1991, Furness et al 1994). Thus, whilst it is built upon survey and surveillance, it is more precise and oriented to specific targets or goals (Hellawell 1991, Spellerberg 1991).

Survey is an exercise in which a set of qualitative observations are made but without any preconception of what the findings ought to be.
Surveillance is a time series of surveys to ascertain the extent of variability and/or range of values for particular parameters.
Monitoring is based on surveillance and is the systematic collection of data or information over time in order to ascertain the extent of compliance with a predetermined standard or position.

The effectiveness of monitoring varies considerably. An effective monitoring program is not necessarily complex nor expensive. Effectiveness is gauged by the relevance and timeliness of the data or information collected which, in turn, are influenced by the design of the program.

A framework for assisting with the design of a monitoring program has been presented by Finlayson (1996a,c). The framework applies to all forms of monitoring (eg changes in the area of a wetland, the ecological health of a wetland, or the underlying reasons behind the loss of wetlands). The framework is not prescriptive. It is not a recipe for a particular type of problem or a particular type of wetland – this would be presumptuous given the many differences between sites, the problems and the resources available. It presents a series of steps that will assist those charged with designing a monitoring program make decisions suitable for their own situation. A person using the framework will make these decisions based on some degree of knowledge and/or expertise. The framework is not a substitute for knowledge or expertise.

Before an effective monitoring program can be implemented the objectives of the program must be clearly identified and agreed. In an ideal situation, this should be a straightforward and cooperative process between managers (who make decisions) and scientists (who provide expert advice and interpret the data). In a simple sense, the managers would outline the need for a monitoring program and the scientists recommend the most appropriate techniques and, by an iterative process, an approach that has both scientific rigour and meets the management objectives will be developed. Conflict could arise if, in outlining the objectives, the managers are constrained or influenced by other than scientific considerations. Under such circumstances it must be remembered that any deficiency in the objectives will influence all other components of the program (Spellerberg 1991).

In a general sense, monitoring is needed to prevent further unchecked exploitation and degradation of wetlands. Thus, there is a need to assess the impact of human development and minimise ecological change. Success in such programs will depend on our ability not only to detect and monitor changes in the quality of wetlands, but also to provide early indications of likely change and thereby take action to prevent this change from occurring. A monitoring program that simply shows that change (including habitat loss) has occurred can have immense educational and public awareness value and demonstrate environmental trends, but programs that enable steps to be taken **before** such change (or loss) occurs are urgently needed. Without these programs the extent of ecological change (and loss) referred to above will continue unabated.

With all monitoring techniques there is a need to establish a starting point or to obtain baseline data that identifies the key functions and values of the site. Thus, the functions and values of a particular site need to be defined. Spellerberg (1991) considers baseline data to be information collected from the same place and on the same basis as subsequent data and that this is different to reference data which may have been collected from the same site by a different method or even from a different site. Reference data should only be used where it is not possible to obtain valid baseline data. To obtain a direct analysis of the extent and ecological significance of change a valid baseline is needed. However, for all sorts of reasons, it may be necessary to use the more indirect method of comparing to reference data. This still has value, but care should be used when inferring from one method to another or from one site to another.

Even a well designed monitoring program could have little value if the information that is collected is not utilised or does not influence the management process for that locality or site. Ideally, the locality or site will be subject to an interactive and holistic management plan that provides the means of responding to the information obtained from the monitoring program. If a formal or official management plan does not exist or is not being effectively implemented it is critical that mechanisms to make use of the information collected from a monitoring program are identified and developed.

The diagram in figure 1 (adapted from Constable 1991) outlines the connection between a formal management procedure and an environmental monitoring program. In this case monitoring provides the means of measuring the output of the management procedure – that is, it provides the means of measuring the (observed) state of the environment and the extent to which it may have been altered. If the management objectives are not being met the existing legislation or regulations that affect the site (or location) are used to adjust the management activities. In the rather ideal procedure shown in figure 1, the monitoring program can be established either before or after a particular management activity is implemented. If monitoring is conducted before a particular management decision is taken it is essential that the information collected is then used to influence the management activities.

7 Management planning

> *'Wetlands are dynamic areas, open to influence from natural and human factors. In order to maintain their biological diversity and productivity and to allow wise use of their resources by human beings, some kind of overall agreement is needed between the various owners, occupiers and interested parties. The management planning process provides this overall agreement.'* (Davis 1993).

In other words, the management plan provides the basis for maintaining the ecological character of a wetland and to allow wise use of the resources by the owner and/or agreed users. In developing a management plan the following issues need consideration:

• It is a way of thinking which involves recording, evaluating and planning and is subject to constant review and revision and is therefore flexible and dynamic.
• It involves three basic steps of describing the features of the site/area, defining operational objectives and taking necessary management actions.
• Preparation of an elaborate plan is not an excuse for inaction or delay.
• Review of the plan may lead to revision of the site description and operational objectives.
• It should be a technical, not a legal document, although it may be supported by appropriate legislation.

Although conditions and resources vary at individual sites the general considerations may be applied widely.

The format of a plan may need to meet various legislative requirements, but it will generally contain a preamble and three major sections (table 3) – description of the site; evaluation and objections; and action plan/prescriptions. Technical staff will normally participate in all three stages with policy staff reviewing the first two stages before approving finances and implementation of the third stage.

The above may sound all very simple, but there are pitfalls, such as making the plan too complicated, making the plan the goal rather than the tool, making the plan inflexible and not allocating resources to ensure the plan can be implemented. Importantly, the plan should provide the means of obtaining and using the information needed for effective management of the wetland.

8 Conclusion

Collation of wetland information for northern Australia has been greatly enhanced in recent years, mainly through the national wetland directory. However, resource and conservation agencies across northern Australia have not agreed a definition of wetlands and a classification system. These steps need addressing before a comprehensive wetland inventory can be successful. Individual jurisdictions may proceed independently and gather inventory information, but this will not provide a national picture. Processes to assist in the development of an inventory are readily available and should be used, after due assessment for local relevance. The inventory will require due attention and agreement on a classification system and be supported by effective monitoring that is dependent on the existence of adequate baseline or reference information.

The information requirements should be identified and supported by a site management plan that ensures that the objective of maintaining the ecological character of a site is supported by appropriate actions. The management plan provides the linkage between processes to gather information and to ensure that it is used in a timely and effective manner.

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Table 1 Wetland classification schemes used in northern Australia

Basis of classification	Region	Reference
Hydrologic	Queensland	Stanton 1975
Vegetation structure and floristic	Australia	Briggs 1981
Hydrologic and vegetation	Australia	Paijmans et al 1985
Physical	Pilbara	Masini 1986
Geomorphic, hydrologic and vegetation	Australia	ANCA 1996
Geomorphic	Australia	Semeniuk & Semeniuk 1997

Table 2 Data categories used by Scott (1993) in the directory of wetlands of Oceania

Category	Information
Title	Name and reference number
Location	Geographical coordinates
Area	Area and/or length of rivers
Altitude	Average
Overview	Summary description of site
Physical features	Hydrology, soils, water quality, climate
Ecological features	Main habitats and vegetation
Land tenure	Ownership of wetland and surrounding land
Conservation measures taken	Details of protected areas
Conservation measures proposed	Further proposals
Land use	Human activities
Possible changes in land use	Development plans and ideas
Disturbances and threats	Existing and possible threats
Hydrological and biophysical values	Principal features
Social and cultural values	Principal values
Noteworthy fauna	Important species
Noteworthy flora	Important species
Scientific research and facilities	Major research activities and facilities
Conservation education	Existing programs and facilities
Management authority and jurisdiction	Responsible authority(ies)
References	Key published literature
Reasons for inclusion	Reason(s) designated as important

Table 3 Recommended components of a management plan (Davis 1994)

Preamble

- Concise statement of broad governmental policies concerned with the plan.
- Statement of the Ramsar obligations of maintaining the ecological character of a listed site

Description

- Establishes the basis for monitoring to identify any subsequent changes at the site.

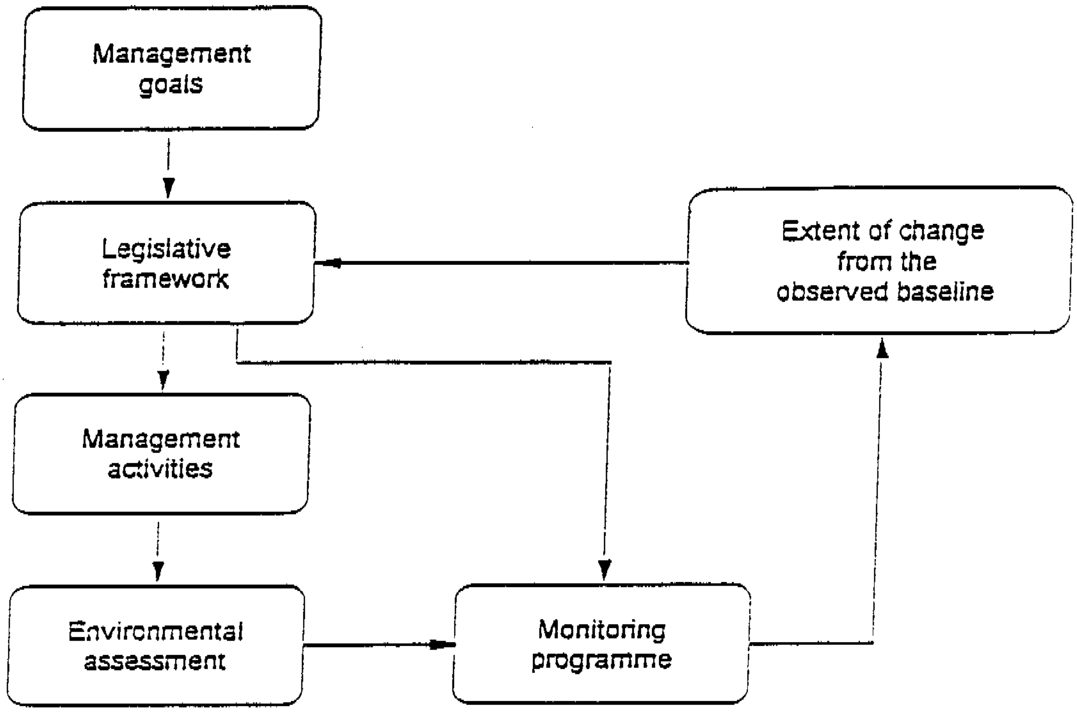
Evaluation and Objectives

- Evaluation
  - Assessment of the major features of the site
- Long-term management objectives
  - Concise expression of intent and derived from the evaluation process.
- Factors influencing the achievement of long-term objectives
  - Internal natural factors such as vegetation succession and variations in water level.
  - Internal human-induced factors such as erosion, disturbance and pollution.
  - External natural factors such as climate change, variations in current and sea level.
  - External human-induced factors such as sedimentation and pollution.
  - Factors arising from legislation or tradition such as treaties or access rights.
  - Physical considerations such as inaccessibility.
  - Available resources such as finance and a skilled workforce.
- Identification of operational objectives
  - Taking into account factors that affect the achievement of long-term objectives.
  - Establishment of the limits of acceptable change.

Action Plan/Prescriptions

- Workplan
  - Provides management options derived from the operational objectives.
- Projects
  - Prescriptions to achieve the individual tasks to required for the operational objectives.
  - Establishes record keeping and administrative procedures.
- Work programs
  - Derived from the individual projects.
- Reviews
  - Assessment of the success of the workplan, projects and work program.

Figure 1 Connection between a formal management procedure (plan) and an environmental monitoring program (based on Constable 1991).



Wetland types and their distribution in northern Australia

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Abstract

The Wet-Dry tropics of northern Australia are sparsely populated. There are few large towns with many small settlements scattered across a vast area. The climate is strongly seasonal with two broad seasons – a cool/warm Dry season and a warm/hot Wet season. As a consequence of the climate, flow in the rivers is strongly seasonal and many cease to flow during the Dry season. The knowledge of wetland types and their distribution is very uneven and a comprehensive inventory does not exist. Generalised wetland maps have been compiled and show a pattern of small permanent lakes and swamps inland and extensive floodplains near the coast. Seasonally or intermittently flooded swamps are located along the coast with intermittent or episodic wetlands inland. At a broad scale these wetlands have been described. The general ecological features of the broad categories of wetlands – coastal salt flats, mangrove swamps, freshwater lakes, floodplains, and freshwater ponds and swamps – are summarised in order to illustrate their immense diversity and ecological values.

Keywords: tropical wetlands, Ramsar Convention, types, distribution, characteristics

1 Introduction

The region considered in this overview of wetland types of northern Australia is shown in figure 1. It comprises the Kimberley in Western Australia (WA), the Top End and Barkly Tableland of the Northern Territory (NT), and the Gulf Plains and Cape York Peninsula of Queensland (Qld). In a general sense, the ecological character of the wetlands has been described and the major threats and management problems identified (Arthington & Hegerl 1988, Finlayson et al 1988, 1991, 1997, Finlayson & von Oertzen 1993, Blackman et al 1993, Fleming 1993, Jaensch & Lane 1993, Jaensch 1994, Singer & Wright 1985, Storrs & Finlayson 1997).

This vast region contains many wetlands, particularly along the coast, and many of these have great conservation value and, compared to wetlands elsewhere in Australia, have retained many of their natural features (Finlayson & von Oertzen 1993, Finlayson et al 1997, Storrs & Finlayson 1997). An account of the major wetland types and their distribution is presented as a background for further analysis of their ecological features and management issues. Before considering the major types of wetlands a brief description of the geographical region, population, climate and drainage pattern is presented.

2 Geographical region

The region being considered (fig 1) roughly corresponds to the Wet-Dry tropics of northern Australia. Landsberg et al (1966) defined the Wet-Dry tropics as those areas with an annual rainfall of 600–1600 mm spread over 4–7 months. Within the Australian context this corresponds to the northern-most part of the continent with a south-eastern extension along the western side of the Great Dividing Range (fig 2). Recent efforts to divide Australia into biogeographical regions (Thackway & Cresswell 1995) have provided a further breakdown of the broad region being considered (the south-eastern extension of the Wet-Dry tropics has not been included).

The interim biogeographical regions (IBRA) were delineated on the basis of climate, lithology/geology, landform, vegetation, flora and fauna, land use and, where necessary, other attributes. The biogeographical regions covered in this review are shown in figure 3 and listed in table 1. Combined they cover more than 2 x 10^6 km^2.

3 Population

Northern Australia is relatively sparsely populated compared to the eastern and south-eastern regions of Australia. The largest population centre is Darwin (77 400) which is also the administrative centre of the Northern Territory. Smaller population centres include Broome (8900), Derby (3000), Kununurra (4000) in Western Australia, Katherine (8300) in the Northern Territory and Weipa (2500) in Queensland (Australian Bureau of Statistics 1996). A large proportion of the population resides in urban areas (70% in the NT). Many smaller settlements are located along major transport routes and in association with pastoral, tourist and recreation and mining activities. Aboriginal people have also established many small settlements known as outstations.

4 Climate

The climate of tropical Australia has been described by Ramage (1971) and Lee & Neal (1984). In general, there are two seasons. The Wet season commences late in the year (November–December) and lasts for 3–4 months; both the onset and duration vary from year to year. Relatively low atmospheric pressure systems develop over northern Australia and the resulting inflow of warm air from the surrounding tropical ocean leads to a hot rainy season. The most significant features of the Wet season are thunderstorms, tropical cyclones and rain depressions. Cyclones occur along the coast during the Wet season and can bring destructive winds, torrential rain, flooding, and sometimes 'storm-surges'. The build-up to the Wet is heralded by thunderstorms with localised, but very heavy rain. Thunderstorms during March–April do not produce prolonged rain and indicate the approach of the Dry season which is characterised by the dry south-east trade winds.

The region has warm to hot temperatures all year round. These temperatures are accompanied by high relative humidity of about 80%. Cloud cover is greatest over the coast during the warm Wet season, decreasing over the dry interior and allowing overnight radiative cooling. The range of temperatures and day length throughout the year are relatively small. Average annual effective evaporation often exceeds rainfall.

5 Drainage pattern

About two thirds of total run-off from Australia occurs in northern Australia (Australian Water Resources Council 1976). The two drainage regions that closely correspond to the Wet-Dry tropics (as defined for this overview) are shown in figure 2. Estimated run-off from these is 91 000 ML y^{-1} from the Timor Sea region and 131 000 ML y^{-1} from the Gulf of Carpentaria region. Both regions have coordinated external drainage to the Timor/Arafura Seas and Gulf of Carpentaria respectively.

The rivers have highly seasonal and variable flows. Many cease to flow during the Dry season and tidal influences can extend some 80–100 km upstream. Some are little more than a chain of elongated waterholes for much of the year. The Gregory and Lawn Hill Rivers in Queensland are perennial. As a consequence of the water releases from Lake Argyle and Lake Kununurra the downstream portion of the Ord River in Western Australia is also now perennial.

A number of dams and reservoirs have been constructed to conserve surface water. The largest is Lake Argyle on the Ord River which has a volume of 5672 M m^3 and a flood storage capacity of 34655 M m^3.

6 Wetland types

The Ramsar Convention for Internationally Important Wetlands defines wetlands as

> *'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which does not exceed six metres'.*

This definition has attracted a large amount of debate and dissatisfaction within Australia (see McComb and Lake 1988) and internationally (see Finlayson & van der Valk 1995). However, given that definitions are derived for specific purposes and that the Ramsar definition is purposefully broad it has been generally more accepted in recent years both within Australia (ANCA 1996) and internationally with deliberate modification for specific purposes (Finlayson & van der Valk 1995).

Within Australia Paijmans et al (1985) have defined wetlands as

> *'land permanently or temporarily under water or waterlogged. Temporary wetlands must have surface water or waterlogging of sufficient frequency and/or duration to affect the biota. Thus, the occurrence, at least sometimes, of hydrophytic vegetation or the use by waterbirds are necessary attributes.'*

This definition does not contain a depth criterion, but is otherwise similar to that used by the Ramsar Convention.

Paijmans et al (1985) considered the frequency and regularity of inundation as an important feature of Australian wetlands. Based on flooding patterns they derived four general groups of wetlands (see below), although the hydrological information base may not always be adequate to accurately differentiate between such wetlands on all occasions.

- Permanent – annual inflow exceeds the minimum annual loss in 90% of years
- Seasonal – alternately wet and dry every year according to season
- Intermittent – alternately wet and dry, but less frequently and regularly than seasonal
- Episodic – dry most of the time with rare and very irregular wet phases

In view of the uneven information base for wetlands in northern Australia the wetland categories used by Paijmans et al (1985) are not used in this overview. Rather, a simplified system is used in line with similar approaches used by Finlayson et al (1998), Fleming (1993) and Finlayson & von Oertzen (1993). Thus, the wetland categories used are coastal salt marshes, mangrove swamps, freshwater lakes, floodplains, and freshwater ponds and swamps. These terms are acknowledged to be imprecise and for some purposes (eg detailed biodiversity analyses) may not be suitable.

7 Wetland distribution

It is not possible, based on current inventory information, to accurately depict the extent of wetlands across northern Australia. Concerted inventory work has occurred in some areas, such as the Gulf of Carpentaria and Cape York Peninsula in Queensland (Blackman et al 1993), but a standardised inventory approach has not been adopted across the entire region. (Whether or not such an approach is warranted is not discussed here, but see Blackman et al (1995) for a discussion on this subject).

Paijmans et al (1985) summarised information derived from 1:250 000 topographical maps and presented this on 1:250 000 000 maps of the entire continent. The maps give a broad indication of wetland distribution but contain many uncertainties and are described by the authors as '*too large, too detailed and too inaccurate.*' They do not specifically illustrate individual wetlands nor depict all wetland categories, but they do illustrate a number of key points about the distribution of wetlands in northern Australia that reflect the general geographic setting:

- there is a general low occurrence of permanent freshwater lakes and swamps
- intermittent freshwater swamps are widespread
- permanent and near permanent wetlands are widespread
- episodic lakes and land subject to inundation by freshwater are not common
- generally dry wetlands are not common.

Further south (outside of this region) the wetlands are drier for longer periods and episodic flooding occurs.

Without a complete inventory that includes much better mapping of wetlands, management for conservation and sustainable utilisation of wetlands will continue on an *ad hoc* basis. The recent directory of important wetlands in Australia (ANCA 1996) lists many wetlands across Australia, but does not provide a base for accurate mapping. Remote sensing has been used for wetland inventory (eg Taylor et al 1995), but it has not been used to produce a comprehensive map of wetlands of Australia.

The wetland types shown in figure 4 give a generalised pattern of wetland distribution in the region that reflects the topography, drainage pattern and rainfall. Along the Queensland coast the upland areas contain permanent and seasonal wetlands – floodplains, lakes, billabongs (oxbow lakes) swamps, waterholes, and river flats liable to flooding. There are also extensive tidal flats and mangroves, some backing on to seasonal swamps. Floodplain lakes, billabongs, and waterholes occur in major deltas. On Cape York Peninsula seasonal swamps in shallow depressions are common while some volcanic craters contain permanent lakes and swamps.

The lowlands along the Gulf of Carpentaria contain intermittent or seasonal swamps in shallow pans, permanent waterholes in channels, seasonal billabongs, lakes and swamps on the upper portions of rivers that drain to the Gulf of Carpentaria. Supratidal flats, up to 30 km inland and with very little vegetation, and narrow intertidal flats with a fringe of mangroves, occur along the coast.

The lowlands surrounding the Arnhem Land Plateau have numerous floodplain lakes, waterholes and swamps along the major rivers, and permanent or seasonal swamps on alluvial plains near the sea. The coastal plains to the east of Darwin contain extensive floodplains along rivers originating from the Arnhem Land Plateau. Coastal wetlands include intertidal flats with mangroves and supratidal flats, either bare or with sparse vegetation. The Kimberley coast is very rugged and coastal wetlands are confined to supratidal flats near large rivers.

8 Wetland characteristics

Much of the information presented below is taken from past reviews of northern Australian wetlands (eg Finlayson et al 1988, Blackman et al 1993, Finlayson & von Oertzen 1993, Jaensch 1994, Finlayson 1995, Jonauskus 1996, Finlayson et al 1997, Storrs & Finlayson 1997).

8.1 Coastal salt marshes

Coastal salt marshes encompass intertidal salt marshes and supratidal salt flats that can extend some 30–40 km inland (Blackman et al 1993). The marshes may be separated from inland salt flats by sand dunes and chernier ridges. Salt marshes occur along the coast and in embayments such as Cambridge Gulf and King Sound in the Kimberley (Semeniuk 1993) and extensively along the Arnhem Land/Gulf of Carpentaria coast (Love 1981, Galloway 1982, Blackman et al 1993). They are characterised by macro-tides (often 5–7 m range) that rise and fall across broad expanses of mudflats or seagrass meadows.

Plant diversity is not high. Overall, tropical salt marshes contain considerably fewer plant species than those in temperate areas (Stanton 1975, Saenger et al 1977, Specht 1981). Salt flats lacking vegetation are more common (Macnae 1966) and are found alongside many of the coastal mangrove communities.

Information on the fauna of these marshes and flats is sparse with the exception of migratory shorebirds. These birds also utilise the mudflats that are exposed at low tide. Watkins (1993) presents population numbers and identifies the south-east Gulf of Carpentaria in Queensland and Roebuck Bay and Eighty Mile Beach in Western Australia as three of the most important areas. These areas have the highest concentrations of waders in the East Asian/Australasian flyway and are important staging sites for migratory birds that go even further afield.

8.2 Mangrove-swamps

Mangroves are halophytic trees or shrubs which dominate sheltered, muddy, intertidal environments along tropical and subtropical shorelines. They range from a narrow coastal fringe to extensive forests and extend more than 40 km inland along rivers, covering about 4120 km^2 in the Northern Territory, 2520 km^2 in Western Australia (Galloway 1982) and a further 1140 km^2 (approx) in the Gulf of Carpentaria and northern part of Cape York (Dowling & McDonald 1982).

The distribution of mangroves along the northern coastline has been investigated reasonably thoroughly with broadscale mapping for much of the coastline and relationships with environmental factors identified (Hegerl et al 1979, Dames & Moore 1984, Semeniuk 1993, Blackman et al 1993). The Alligator Rivers Region and Darwin Harbour have received possibly the greatest amount of attention (Hegerl et al 1979, Wells 1985, Dames & Moore 1984, Davie 1985, Finlayson & Woodroffe 1996) in the Northern Territory. Semeniuk (1993) provides an overview of much of the information for the Kimberley coast while in the Gulf of Carpentaria and Cape York Peninsula much of the data is either incomplete or not collated (Blackman et al 1993).

The mangroves of the Kimberley coast are species rich with similar species assemblages to those in the Northern Territory (Semeniuk 1993). For example, on muddy tidal flats there may be a zone of *Sonneratia alba*, then *Avicennia marina*, *Camptostemon schulzii*, *Rhizophora stylosa* and finally a landward mixed zone of *Avicennia marina*, *Aegialitis annulata*, *Bruguiera exaristata* and sometimes pure stands of *Ceriops tagal*. Semeniuk (1993) also describes the geomorphic differences between habitats such as Cambridge Gulf, King Sound and the remainder of the Kimberley coast. Blackman et al (1993) identifies the major mangrove sites along the Gulf of Carpentaria and Cape York Peninsula coast. These include the Nicholson River delta and the Mitchell River Fan aggregation in the Gulf, and the Jardine River wetlands and the Newcastle Bay complex on the Cape.

In general, mangrove forests vary from having distinct vegetation zones to being completely mixed, with the frequency of inundation by tidal water, fresh-water flow, soil type and drainage being important controlling factors (Bunt et al 1982, Semeniuk 1993). Probably the most common species is *Avicennia marina* which can tolerate a wide salinity range (Macnae 1966) and is a pioneer species commonly found on newly formed mudbanks in estuaries or on riverbanks. Semeniuk (1993) reports that there is a gradation from forests in the seaward parts of mangrove formations to scrub and heath in landward parts. Regional factors (coastal setting, climate and tidal range) that are inter-related influence the nature of mangrove habitats in any location.

Mangroves are very productive, but except for Darwin harbour (see Woodroffe & Bardsley 1988, Woodroffe et al 1988) there is little information on the primary productivity of these communities in northern Australia.

The mangrove fauna, especially the macroinvertebrates, are not as well known as the flora (Hanley 1995). Relatively few surveys have been undertaken across the range of habitats. The larger animals are better known, but not necessarily in a quantitative manner. The saltwater or estuarine crocodile (*Crocodylus porosus*), a number of snakes, lizards, geckos, skinks and turtles plus mammals such as the fruit and insect-eating bats, water rats, feral buffaloes, pigs and cattle are known to utilise mangrove habitats (Hegerl et al 1979, Milward 1982). List of biota in Australian mangrove-swamps are given by Saenger et al (1977) and Hutchings & Recher (1983) while Hanley (1995) discusses the invertebrate fauna of a few sites in northern Australia. The best known animal species is the estuarine crocodile.

8.3 Freshwater lakes

Finlayson & von Oertzen (1993) report that the classification and delineation of permanent waterbodies in tropical Australia is confused. The terms billabongs, waterholes, lagoons and ponds are used interchangeably. Further, there is a strong temporal pattern associated with such habitats that is not fully understood. The permanent waterholes that are features of many northern rivers – eg the Nicholson and Gregory Rivers, Queensland (Blackman et al 1993) – are not considered with the lakes, but with the freshwater ponds (see below).

Permanent and seasonal lakes are rare in northern Australia (fig 4), only occur near the coast and are often associated with floodplain and dune ecosystems (Paijmans et al 1985, Blackman et al 1993). Artificial lakes are an important feature of the region. They vary in size from small stock-watering dams (or tanks) to the extremely large Lake Argyle on the Ord River. Fogg Dam is a permanent lake near Humpty Doo in the Northern Territory that was built to retain water for the ill-fated rice development scheme (Mollah 1982). It is relatively shallow and contains many water plants, including the alien weed *Eichhornia crassipes*. To a large extent the flora and fauna of Fogg Dam is similar to that described for the permanent swamps and floodplains along the northern coastal zone.

Lake Argyle has great conservation value (Graham & Gueho 1995) in what was otherwise a fairly dry environment. The Ord River downstream from the lake now flows all year round. Along with Lake Kununurra it has become a significant drought refuge for waterbirds and a migration stop-over for many species (Jaensch & Lane 1993).

8.4 Floodplains

General Information

Seasonally and intermittently flooding plains occur along most rivers that are influenced by monsoonal rains and have a very pronounced seasonal inundation cycle. The floodplains vary in size and occur across all of northern Australia. Those between Darwin and Arnhem Land have probably been the centre of more investigation and controversy than the others due to conservation, mining, weed and saline intrusion problems (Fox et al 1977, Finlayson et al 1988, Finlayson & von Oertzen 1993, Jonauskus 1996).

The northern climate and hydrology have a strong influence on the floodplains. The permanent waterholes (often inaccurately called billabongs) have fairly uniform physico-chemical conditions during periods of stream flow and a progressive increase in solute concentrations during the Dry season. Detailed accounts are presented in Walker & Tyler (1984), Bishop & Forbes (1986) and Morley et al (1984) and summarised in Finlayson et al (1990).

Plants

Detailed vegetation surveys have been undertaken on the floodplains between Darwin and the East Alligator River (eg Story 1976, Williams 1979, Burgman & Thompson 1982, Sanderson et al 1983, Taylor & Dunlop 1985, Bowman & Wilson 1986, Finlayson et al 1989, 1990, Whitehead et al 1990). In the Northern Territory a broadscale vegetation survey of the major floodplains between the Moyle River in the west and the Glyde River in the east was undertaken in 1990 (Wilson et al 1991). A detailed floristic survey of the Arafura Swamp has recently been undertaken, however other areas of Arnhem Land have not been surveyed in detail. Further surveys and collation of data are required for the Gulf of Carpentaria and Cape York Peninsula to supplement the information reported by Blackman et al (1993). Jaensch & Lane (1993) have reported on the floodplains of the Kimberley region.

General descriptions of the distribution of the major plant species on the floodplains in the Northern Territory can be made from various surveys (Wilson et al 1991). *Oryza rufipogon (meridionalis)* grasslands and *Melaleuca* spp. woodlands are extensive and spread across most, if not all of the floodplains. The sedges *Eleocharis* spp. and *Fimbristylis* spp. and the water lilies *Nymphaea* spp. and *Nymphoides* spp. are also common. The grass *Pseudoraphis spinescens* is not common outside of the Adelaide-Alligator Rivers floodplains. The weeds *Mimosa pigra* and *Salvinia molesta* have become prominent features of some floodplains.

A detailed analysis of aquatic plant distribution is available for the Magela Creek floodplain in the Northern Territory (Morley 1981, Williams 1979, Sanderson et al 1983, Finlayson 1988, 1993, Finlayson et al 1989, 1990). The general classification presented by Finlayson et al (1989) is listed as an example of the diversity of habitats that occur on these plains: *Melaleuca* open forest and woodland; *Melaleuca* open woodland; *Nelumbo* swamp; *Oryza* grassland; *Hymenachne* grassland; *Pseudoraphis* grassland; *Hymenachne-Eleocharis* swamp; mixed grassland and sedgeland; *Eleocharis* sedgeland; and open-water community. Whilst not as rigorous as that proposed by Sanderson et al (1983) this classification allows for seasonal and annual changes in vegetation associations and dominance.

An outstanding feature of the floodplain vegetation is the variation in floristic composition and foliar cover during the Wet and Dry seasons (Finlayson et al 1989, 1990). The success of the majority of species relies on mechanisms that enable them to survive the Dry season drought (Finlayson et al 1989, 1990, Finlayson 1993).

Animals

Examination of available data reveals that the Northern Territory floodplains hold high numbers of animals (Finlayson et al 1988). These include freshwater and saltwater crocodiles (Bayliss et al 1986, Messel & Vorlicek 1986), other large reptiles such as the file snake (Shine 1986) and freshwater turtles, freshwater fish (Bishop et al 1986), freshwater mussels (Humphrey & Simpson 1985) and a wide assortment of water birds (Morton & Brennan 1986, Morton et al 1993a,b). When taken in conjunction with the sizes of the animals, these data convey the reality of a high standing biomass. It is expected that the same reality will apply to floodplains across northern Australia given reports on populations of at least some sectors of the fauna (Blackman et al 1993, Jaensch & Lane 1993).

The floodplains have a relatively low mean nutrient availability (Morley et al 1984) and are temporally and spatially variable. They are, however, dynamic with plant standing crops developing very rapidly at the start of the Wet season and senescing and decomposing at the beginning of the Dry season (Finlayson 1990). Large long-lived animals exploit the wetlands by using a high level of mobility and/or by having mechanisms that allow them to withstand periods of little or no nutrient intake.

Animals lacking the mobility to be successful in exploiting sequences of highly productive periods are faced with food shortages, at least on a seasonal basis. Large aquatic reptiles in the region exhibit either or both a physiology of periodic or constant low metabolism and slow growth rates, or food habits that lower their dependence on foods provided by the aquatic environment (Seymour et al 1981). *Crocodylus johnstoni* (freshwater crocodile) eats less during the Dry season than during the Wet season, particularly when the temperature is lower (Webb et al 1982) and approximately 40% of their food comes from the terrestrial environment. Freshwater turtles and adult *Crocodylus porosus* (saltwater crocodile) also depend heavily on foods of terrestrial origin. Smaller *Crocodylus porosus* are opportunistic feeders and mainly eat invertebrates (Taylor 1979). The Arafura file snake (*Acrochordus arafurae*) reproduce less frequently than other snakes (Shine 1986) and possess a metabolic rate that is lower than most other reptiles (Seymour et al 1981, Shine 1986).

Morton & Brennan (1986) and Morton et al (1990a,b, 1993a,b) provide a biogeographical description of the birdlife of monsoonal Australia. The freshwater wetlands are the prime habitat for 68 species, the adjacent grass/sedgelands for 26 species and the *Melaleuca*-dominated riparian forests for 20 species, which together comprise 45% of the Top End bird species. The numerically dominant species on the floodplains are *Anseranas semipalmata* (magpie goose), *Dendrocygna arcuata* (wandering whistling duck), *Egreta intermedia* (intermediate egret) and *Plegadis falcinellus* (glossy ibis). There are also an additional 18 species of migratory birds from the Charadriidae and Scolopacidae families, though few are resident. Unlike other habitats the wetlands have a predominance of piscivores, herbivores and species that consume aquatic invertebrates.

Seasonal movement of waterbirds is very pronounced with species migrating between wetlands on a seasonal basis (Morton & Brennan 1986, Jaensch 1995) and from and to both the northern hemisphere and southern Australia. The magpie goose is the best known and most abundant of the waterbirds and the complex interactions that determine its migratory pattern are discussed by Morton & Brennan (1986). In broad terms, they move to swamps that supply their nesting requirements in the Wet season, and during the Dry season they are influenced by the availability of food and water. Broad scale, seasonal changes in distribution occur for other wetland birds, such as *Tadorna radjah* (radjah shelduck) and *Dendrocygna arcuata* and *Dendrocygna eyloni* (the whistling ducks) (Morton et al 1990b, 1993a,b).

Some freshwater fish are dependent on food entering the aquatic environment from terrestrial sources. These include surface feeding species like *Melanotaenia splendida inornata* and *Melanotaenia nigrans* (chequered and black-striped rainbow fish) as well as such highly specialised species as *Toxotes chatareus* and *Toxotes lorentzi* (the archer and primitive archer fish). Other species, such as *Hephaestus fuliginosus* (black bream) and *Syncomistes butleri* (sharp-nosed grunter), scavenge on material of terrestrial origin, while the fork-tailed catfish (*Hexanematichthys leptaspis*) is omnivorous.

Of the larger species, *Lates calcarifer* (barramundi) exhibits great mobility, breeding in sea water at the mouth of the river system and then either staying in the salt water or swimming upstream to the fresh water. The juveniles spend their early weeks in brackish coastal swamps, some migrating upstream to the freshwater floodplains. Fish migration occurs during the Wet season (Bishop et al 1995). Recolonisation of the lowland sandy creeks and backflow billabongs in the early-Wet results in the most obvious seasonal changes in fish community structure. Movement occurs in both an upstream and downstream direction from Dry season refuge areas on the floodplains and upper escarpment areas.

8.5 Freshwater ponds and swamps

The uncoordinated drainage lines characteristic of the Barkly Tableland terminate in or have associated with them wetlands which are flooded frequently enough to support distinctive swamp communities. The Barkly Tableland lies on the southern edge of the monsoonal belt and contains intermittently flooded swamps that receive some rain in most years. Freshwater swamps also occur in the Kimberley (eg Lake Kununurra, Parry floodplain – Jaensch & Lane 1993), Gulf of Carpentaria (eg along the Nicholson and Gregory Rivers) and Cape York Peninsula (along the Archer and Jardine Rivers) (Blackman et al 1993).

Detailed descriptions of these areas are not available, though general reports such as that by Perry and Christian (1954), Jaensch & Lane (1993), Blackman et al (1993) and Jaensch (1994) list plant species and provide general information on seasonal changes and hydrology. In general, the drier areas are treeless except for small areas of *Eucalyptus microtheca* (coolibah) woodland, while the stream channels are fringed with *Muehlenbeckia cunninghamii* (lignum). The larger swamps contain assemblages of plants and animals similar to those described for the floodplains.

The summer filling of the swamps provides breeding areas for water birds such as *Anseranas semipalmata* (magpie goose), *Malacorhynchus membranaceus* (pink-eared duck) and *Dendrocygna eytoni* (plumed whistling duck), 'staging' grounds for migratory waders and 'summering' areas for *Glareola maldivarum* (oriental pratincole). The bird populations are immense and vary spatially and temporally. The long-haired rat *Rattus villasissimus* utilises the intermittent swamps as refugia and during good seasons will rapidly breed to plague proportions (Carstairs 1976).

9 Conclusion

The major wetland types of northern Australia have not been well mapped. The only comprehensive maps available are generalised and show wetland distribution derived from topographical maps. There is a general low occurrence of permanent freshwater lakes and swamps, intermittent freshwater swamps are widespread, permanent and near permanent wetlands are widespread, episodic lakes and land subject to inundation by freshwater are not common, and generally dry wetlands are not common. Given the uncertain information base the following categories of wetlands are used, whilst recognising the imprecise nature of many of the terms – coastal salt marshes, mangrove swamps, freshwater lakes, floodplains, and freshwater ponds and swamps.

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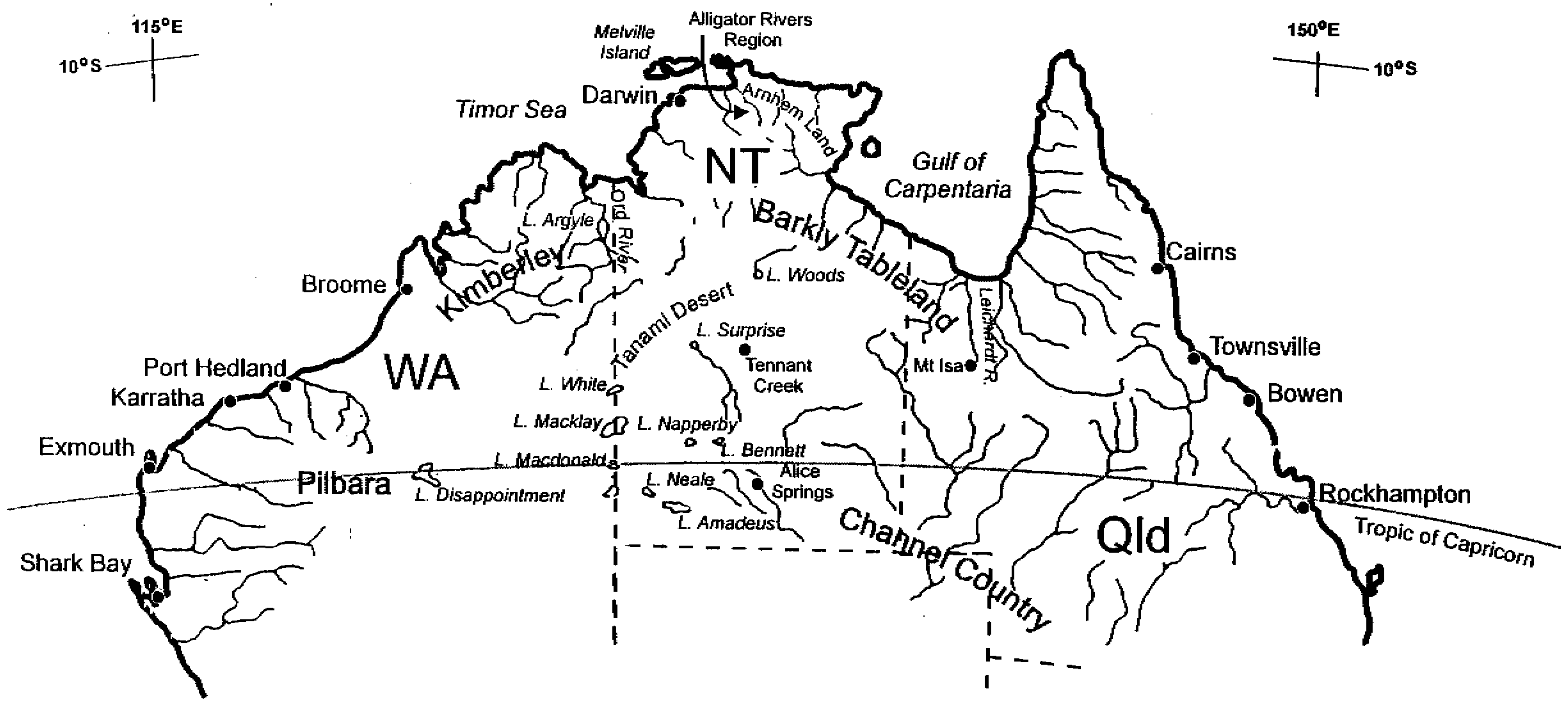
Table 1 Biogeographical regions within the area of northern Australia known as the Wet–Dry tropics (information from Thackway & Cresswell 1995)

Biogeographical region	Codes	Area (km^2)	Description
Burt Plain	BRT	71809	Plains of low rocky ranges of Pre–Cambrian granites with mulga and other acacia woodlands.
Central Arnhem	CA	36898	Gently sloping terrain and low hills on Cretaceous sandstones and siltstones and laterised Tertiary material; yellow earthy sands and shallow stony sands; open forest and woodland with grass understorey.
Central Kimberley	CK	76907	Hilly to mountainous with skeletal sandy soils supporting hummock grasses and scattered trees.
Cape York Peninsula	CYP	115477	Low hills and plains, tropical humid/marine; woodlands.
Daly Basin	DAB	20921	Gently undulating plains and scattered low plateau remnants on Palaeozoic sandstones, siltstones and limestones; neutral loamy and sandy red earths; open forest with perennial and annual grass understorey.
Dampierland	DL	89595	Mix of sandplains, coastal and alluvial plains and limestone with a dry hot tropical climate. Vegetation includes hummock grasses, samphire and scattered woodland.
Gulf Fall and Upland	GFU	118975	Undulating with scattered low hills with skeletal soils and shallow sands. Woodland to low woodland with spinifex understorey.
Great Sandy Desert	GSD	394599	Mainly tree steppe with open hummock grass and scattered trees and shrubs. Undulating uplands with shrubs.
Gulf Coastal	GUC	27807	Gently undulating plains with scattered rugged areas. Woodland with spinifex understorey.
Gulf Plains	GUP	211584	Marine and terrestrial deposits of the Carpentaria and Karumba basins; plains, plateaus and outwash plains; woodlands and grasslands.
MacDonnell Ranges	MAC	36986	High relief ranges and foothills covered with spinifex hummock grassland, sparse acacia shrublands and woodlands along watercourses.
Northern Kimberley	NK	87017	Dissected plateau with savanna woodland and riparian closed forests. Mangal in estuaries and closed embayments.
Ord–Victoria Plains	OVP	125177	Level to gently undulating plains with scattered hills. Skeletal soils with grasses and scattered trees.
Pine Creek Arnhem	PCA	51576	Hilly to rugged with skeletal soils. Woodland with sorghum understorey.
Sturt Plain	STU	99719	Gently undulating plains on laterised Cretaceous sandstones; neutral sandy red and yellow earths; woodland with spinifex understorey.
Tanami	TAN	316656	Sandplains with hills and ranges. Mixed shrub steppe with hummock grasses.
Top End Coastal	TEC	68681	Gently undulating with low plateaux. Open forest and woodland with sorghum understorey. Mix of soils.
Victoria Bonaparte	VB	72970	Marine sediments with samphire–sporobolus grassland and mangal. Red earth plains with open savanna of high grasses.

Figure 1. Geographical setting of northern Australia showing major rivers and lakes and population centres (from Finlayson & von Oertzen 1993).



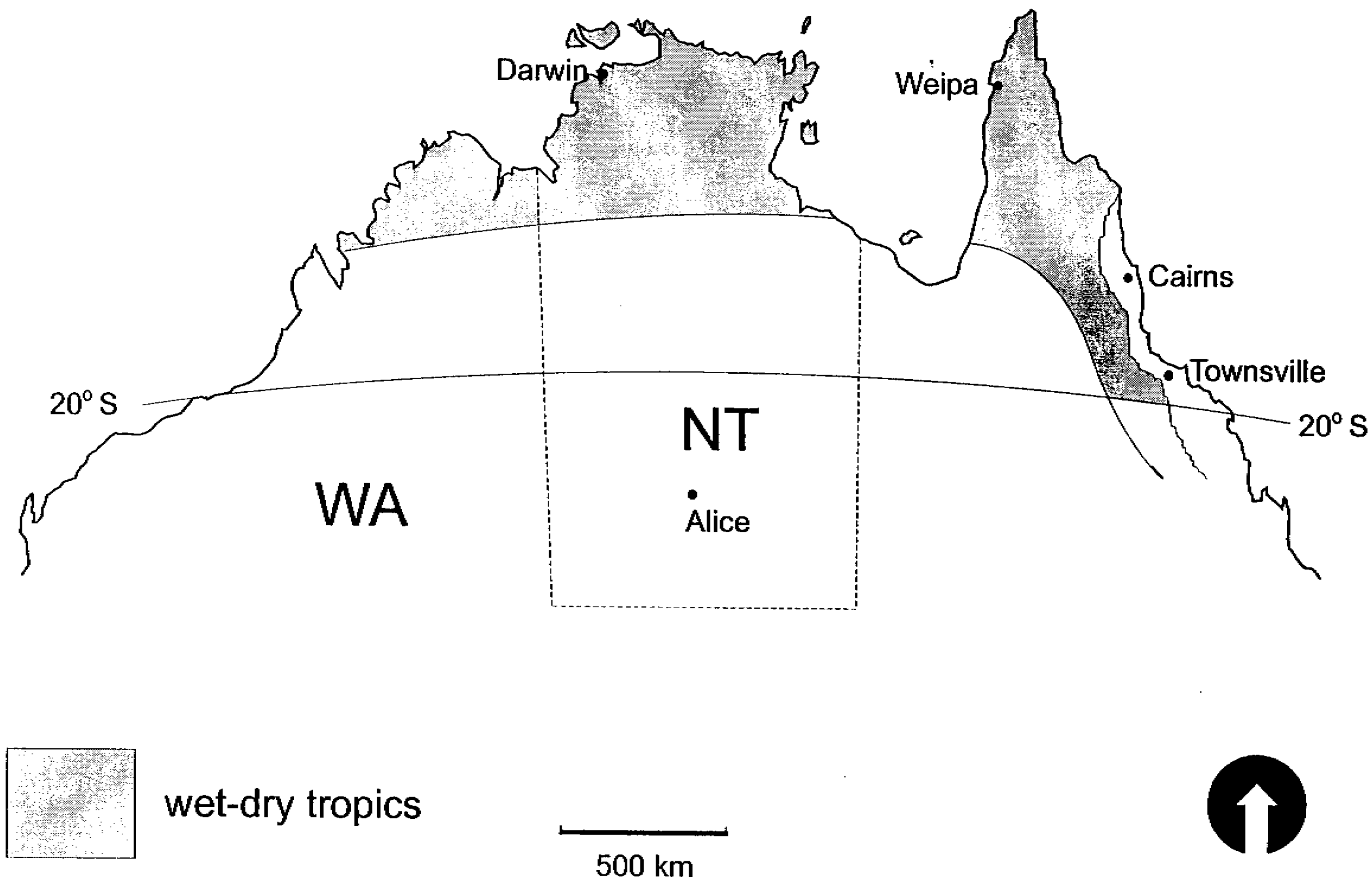


Figure 2 Location of the wet-dry tropics in northern Australia (from Finlayson 1995)

Figure 3. Biogeographical regions (above the dark line) considered in this review of wetland issues in northern Australia (from Thackway & Cresswell 1995). An explanation of the codes used for the regions is given in table 1.

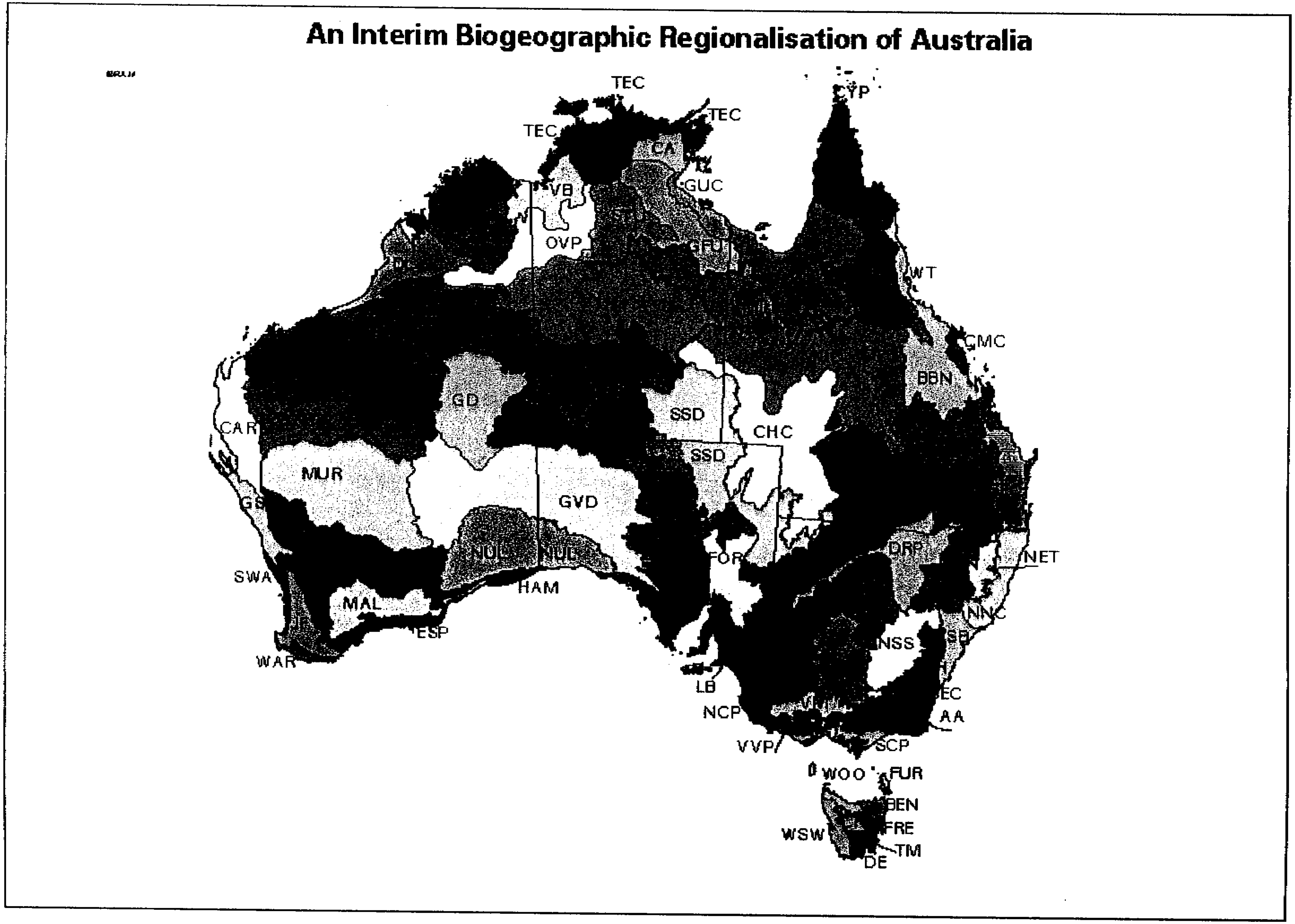
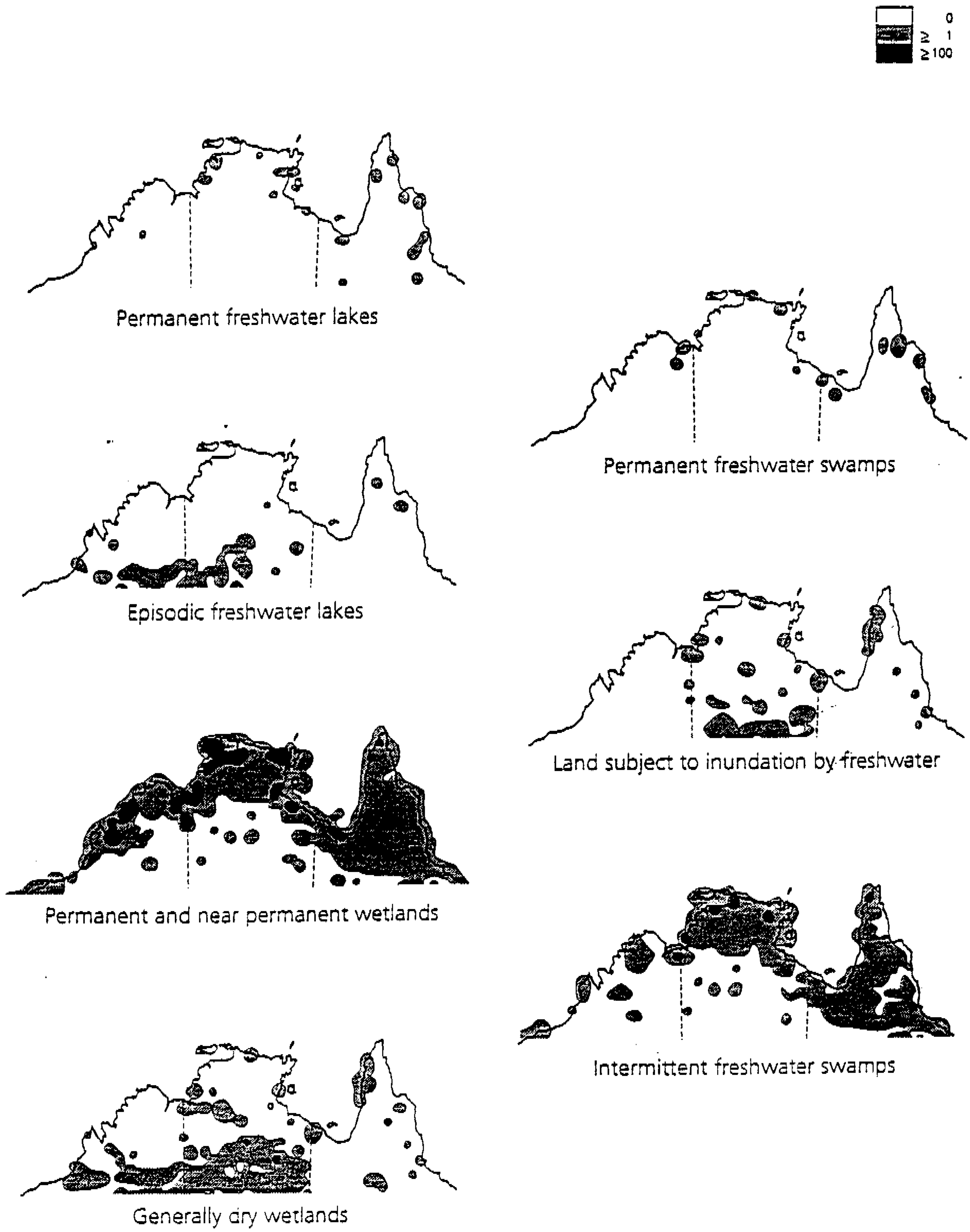


Figure 4. Distribution of wetlands in northern Australia based on Paijmans et al (1985). The code show the frequency of wetland occurrence on 1:250 000 maps.



Some important ecological features of wetlands in the Wet–Dry tropics of northern Australia

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Abstract

The coastal fringe of the Northern Territory is dominated by a vast area of seasonally-inundated wetlands, formed only about 2000 years ago and subject to the climatic extremes of the Wet-Dry tropics. The Wet season extends from October to April. This is followed by a long Dry season during which many creeks cease to flow and dry out. Whether a wetland is permanent (retains surface water) or seasonal (dries out completely) has important ecological consequences. The implications for species distribution and diversity, endemism and the reproductive and survival strategies of aquatic biota in the Wet-Dry tropics are important background information for wetland managers.

Keywords: Wet-Dry tropics, wetlands, ecological processes, biogeography, life-history strategies

1 Introduction

The purpose of this paper is to provide wetland management students with some background to the ecology of wetlands in the Wet–Dry tropics and to flag some management issues that may not be addressed elsewhere in the course. It is of necessity, brief and therefore cursory, but we hope it is also useful in giving students a feel for the dramatic ecological dynamics of these wetlands and a helpful starting point for inquiry into these special places.

The vast area of seasonally inundated wetlands that is such a prominent feature of the coastal zone of the Top End of the NT is a very recent development in terms of geological and evolutionary time scales. At the time of the last glacial maximum, about 20 000 years BP, the sea level was 130 m lower than today (Williams 1991). The coastline was well out to sea from most places and surrounded New Guinea (figure 1). At that time, there was a large lake in the Gulf of Carpentaria into which drained rivers from New Guinea and Australia. The present lowlands probably then contained few extensive lentic wetlands. As sea levels rose with the glacial decline, the coastline moved inland, presumably with an advancing fringe of marine wetlands, reaching its maximum extent approx 6000 BP. These events are mirrored in the rock art of the Arnhemland region (Chaloupka 1983): prior to 6000 BP the art depicts only freshwater fish species and magpie geese are absent. Barramundi and fork-tailed catfish appear after that, indicating the breaching of dispersal barriers to euryhaline and diadromous species in the rivers by rising seawater. More recently, about 2000 BP, magpie geese appeared in the art and this coincides with the development of the present freshwater wetlands. This change to freshwater wetlands was caused by sediment deposition raising the bottom of inundated areas, development by fluviatile processes of levees along the estuary to impound freshwater and attenuation of tidal height by coastal processes at creek mouths. The present threat to these wetlands from saltwater intrusion appears to be a reversal of these processes.

Extensive coastal freshwater wetlands such as these in the NT occur also on Cape York in Queensland and most likely have similar origins. Freshwater wetlands are less well developed on the rivers of the lower Gulf and the Kimberley region. This may in part be a result of lower rainfall but in the Kimberley region the topography is also not conducive to floodplain development.

2 Climate and hydrology in the Wet-Dry tropics: some biotic responses

The highly seasonal rainfall pattern of the Wet-Dry tropics is the major feature influencing the ecology of wetlands of the region. The typical pattern of rainfall and runoff is shown for the Top End in figure 2. The rainfall period here extends from September to June. The runoff period starts 2–3 months later in late November to mid December. The 4–5 month Dry season with very little or no rain results in only seasonal inundation of the floodplain and seasonal flow in many rivers in the region.

Stream flow continues for some months after rain ceases but at a steadily declining rate. This period is termed locally as the 'tapering-flow' or 'recessional-flow' period. The 'runoff season' referred to by barramundi anglers is quite different to that referred to above and is the period from the middle of the Wet season (late February) to the early Dry (early May) when floodplain water drains from the floodplains into the tidal river channels.

Inundation of the floodplains occurs by both direct rainfall and runoff from feeder streams. Inundation by direct rainfall can start occurring as soon as the cracking clay soils are moistened and sealed and this may occur well before runoff starts. In general, the floodplains closer to the coast are inundated by direct rainfall and the more inland floodplain reaches by runoff.

The timing of rainfall events and the amount of rain can vary considerably among years but there is always some rain, unlike many other parts of the continent (figure 3). The period for which the floodplain remains inundated can, therefore, vary greatly from year to year and also between sites depending on topography (figure 4). This spatial and temporal variation has enormous consequences for the wetland biota, determining both the plant assemblage composition and the production and recruitment success of floodplain fauna. Examples of this are:

- Griffin (1995) has shown that recruitment of barramundi is greater in years of high rainfall;
- At ***eriss*** it has been shown that the recruitment of chequered rainbowfish (as measured by upstream migration) to be related to the amount of discharge in December in Magela Creek. ie how early the floodplain is inundated and is therefore available as breeding, feeding and nursery grounds (Pidgeon et al in press) (figure 5);
- the year class strength of freshwater mussels is related to total Wet season discharge (Humphrey & Simpson 1985) (figure 6);
- And the breeding success of saltwater crocodiles and magpie geese can be greatly influenced by flood events affecting nests and eggs.

Clearly, both the pattern of rainfall and the total amount of rain have important consequences for the biota. Being able to interpret these relationships, and even predict outcomes from them, would be an important aid for wetland managers.

An idea of the natural inter-annual variation in populations and communities can assist in deciding whether any changes detected in monitoring programs are of any real concern. A measure of this variability is the 'persistence' of the community. *Persistence* is the tendency for the species composition of a community to remain the same (Giller et al 1994). Increased temporal variability in stream flow and large fluctuations in annual rainfall and water availability all lead to reduced persistence in macroinvertebrate communities. With the reliable occurrence of rainfall in the Wet-Dry tropics it might be expected that persistence would be higher than for the semi-arid regions of southern Australia.

An example of extreme persistence, which might support this idea, was found with fish in one permanent pool in the upper reaches of Gulungul Creek, near Jabiru NT. Species abundance data gathered in the mid-Wet season each year for 8 years were very highly correlated (P <1/200,000) (Humphrey et al 1990). Unfortunately there were no data from elsewhere in Australia to compare with this.

However, a recent examination of persistence of macroinvertebrates in streams around Australia has been undertaken by Humphrey et al (1997) (figure 7). This showed that, as might be expected, persistence of macroinvertebrate communities is significantly and positively correlated with permanence of stream flow, and negatively correlated with interannual variability of annual stream discharge. However, there is also a tendency (only) for macroinvertebrate communities of permanent streams in temperate Australia to be more persistent than those in tropical regions. It is possible that this is related to individual life spans being much shorter in the tropics (many insects live for only a month in tropical waters whereas lifespans of 6 months to 3 years are common in temperate waters). The longer life spans increase the probability that at least some of the species may survive a disturbance, such as inadequate flow, in isolated refugia.

3 Major wetland habitats

The broad classification of wetland habitats in the Wet-Dry tropics include coastal saltflats, mangrove swamps, freshwater lakes, floodplains, freshwater ponds and swamps. Adding rivers to this list covers all the components present in a wetland system that are, at some time, inter-connected. From an ecological point of view, the most important subdivision of these categories is into permanent and seasonal water bodies. Most of the floodplains and lowland stream channels are inundated seasonally and dry out each Dry season, leaving only small areas of permanent water for aquatic organisms to survive in. These permanent water bodies are the deeper billabongs of the floodplain zone and the lowland stream channels, and the pools and shallow channel sections of permanently flowing headwaters of streams rising from rocky plateaux such as Arnhemland and Litchfield. In the Magela Creek system, a tributary of the East Alligator River, there are 210 km^2 of seasonal habitat and, in some years, only about 3 km^2 of permanent water to act as refuges for biota that require surface water to survive.

On a temporal scale, many wetlands spend more of their time as dryland systems than as wetlands. Consequently, dryland processes such as fire and grazing will be important considerations in the management of these areas.

4 Annual cycle of ecological processes

The natural wetland habitats of the Top End that have been most intensively studied to describe their ecological character (biotic structure and processes and environmental processes) are the floodplain and lowland billabongs. The following account is based largely on this work on those water bodies in the Alligator Rivers Region.

4.1 Water chemistry

After the first flush of water in the Wet season, surface waters in the region generally have very low levels of dissolved solids reflecting the highly leached land surface of the region (EC range 5–20 uS/cm). The waters are slightly acidic (pH 5.2) with a very low buffering capacity and generally very clear with low levels of suspended solids (5–60 mg/L). The soft, acidic water probably contributes to a low diversity of molluscs in the region (C. Humphrey, pers com). With each flood event, there is a further general decline in the concentration of solutes (Hart et al 1987a). Most of the surface water at this time is derived from surface runoff (or direct precipitation on parts of the floodplain) rather than ground water. Consequently, the proportions of major ions of surface waters closely resembles that of local rainwater (figure 8). Plants and soil remove over 90% of P, NH_4 and NO_3 from rainwater (Hart et al 1987b).

During the Dry season the water chemistry changes and the pattern of change varies with different kinds of waterbodies. The spring-fed permanent headwaters and the deep channel billabongs change very little over the year. On the other hand, the standing waters of the shallower floodplain billabongs and backflow billabongs of the lowlands evaporate to some extent and concentrate their dissolved salts steadily during the season. In some billabongs the addition of ground water from seepage may cause the solutes to increase ten-fold or more. As the waters concentrate there is a steady progression towards the composition of seawater (Walker and Tyler 1982). In some billabongs there is a sudden marked rise in EC at the end of the Dry season (figure 9). pH also rises slightly over the Dry.

When flow begins early in the Wet season the composition of the first flush water depends on the manner in which it arises. When the downstream progression is at a steady pace the advancing water may develop a front with high solute concentrations leached from the soils over which it passes and the pH may also be quite low (3.5–4.5). Consequently, when this mixes with the water in the billabongs, the water quality for the biota may be very unfavourable for a time until it is diluted by following, more dilute, waters. In some floodplain areas with jarosite soils, oxidation of sulphide to sulphate occurs after the soil becomes wet again after drying out during the Dry season and allowing aeration of the soil. This causes very acidic conditions in the soil water and this allows aluminium to dissolve. High levels of aluminium and sulphate can then be leached from the soil by the slowly advancing water and transported to billabongs. When this happens the water is potentially toxic to fish and mass fish kills may occur (Noller 1983). These kills are invariably associated with very low oxygen levels in the water which is probably also caused by the influx of organic matter with the new water. Fish kills can also occur at this time solely from oxygen depletion resulting from influx of organic matter with storm events (Townsend 1994).

When, as often happens, the first flush occurs as a large flood with rapid progression across the floodplain, there is less potential for these harmful conditions to arise.

4.2 Primary production patterns and nutrient cycling

With the exception of an initial short-lived pulse of algal production at the start of the Wet (Humphrey & Simpson 1985), during the Wet the combination of low nutrients and flushing flows prevents development of large populations of phytoplankton (Walker & Tyler 1983). As flows cease and the Dry season commences, nutrient levels rise (from about June).

Primary production consequently increases until water levels drop enough to allow wind induced resuspension of fine sediments. In some billabongs, this results in a high turbidity from tripton (non-living suspended fine particles) which in turn reduces the amount of light penetration and primary production.

In seasonal water bodies growth and production of submerged and emergent aquatic macrophytes begins in the early Wet season each year when dry ground becomes saturated by rain or floodwater. Maximum biomass of the dominant grasses occurs in the late Wet–early Dry season (Finlayson 1991). With the senescence of these plants there is a large increase in decomposing detritus. In some billabongs this decomposition results in the water becoming anoxic for a period (Walker & Tyler 1983) and this can also be a cause of fish kills.

4.3 Oxygen and temperature

Surface water temperature averages around 30°C but may range from 25°C to 38°C depending on location and time of year. Highest temperatures are recorded late in the Dry season. Thermal depth gradients are typically absent during the Wet season but frequently develop during the Dry. There is some diurnal variation in this gradient as surface waters cool at night. However, even small temperature differences of 1–2°C may be sufficient for stratification to occur (figure 10) and this can cause deoxygenation of deeper waters (Hart & MacGregor 1980). This happens in many billabongs.

Dissolved oxygen levels are generally at their lowest levels at dawn after a night of steady oxygen consumption by respiration by the aquatic community and before any photosynthesis has occurred to produce more oxygen in the water. Oxygen levels typically then begin to rise soon after sunrise and reach maximum levels around mid afternoon. There are not many data on the frequency with which total oxygen depletion occurs by this process, but it has been observed on a number of occasions. When it occurs many fish species can be seen gulping at the water surface flushing their gills with the oxygenated surface film of water. The effect of these short periods of anoxia on fish have not been examined in detail. Fish can recover from short periods of this stress but more frequent and prolonged periods may have more harmful effects. Barramundi have been observed to jump out of the water and strand themselves on fringing vegetation in response to this oxygen depletion (Pidgeon et al 1997).

4.4 Nutrient budgets

As well as the intrinsic aesthetic value of their vegetation and bird life, floodplain wetlands have been considered to play a major role in the 'economy' of the entire river system. The 'flood-pulse' concept proposed by Junk et al (1989) stemmed from observations that the most productive riverine fisheries in Africa were on rivers with extensive floodplains. The concept suggests that the seasonal pulsing of floods over dry ground results in a more rapid recycling of nutrients and organic matter than occurs in permanently wet or dry areas and hence results in much higher productivity than would occur from the increased area of habitat alone. Obviously many fish species in the tropics have adapted to taking advantage of this production.

The applicability of this concept to Australian river systems has not been widely considered to date. Direct evidence from water chemistry may be difficult to obtain as nutrients are rapidly taken up by the biota so that evidence would have to come from biotic responses.

Some support is offered by the observation by Griffin (1995) on barramundi. The past commercial barramundi catch rate in the Mary River system, which is dominated by extensive coastal floodplains with prolonged periods of freshwater inundation, was much higher than in rivers such as the Adelaide River, where the floodplain inundation period is relatively brief.

Freshwater mussels in Magela creek display a bimodal pattern of change in condition over the year. There is a major increase related to the plankton production of the Dry season and a second peak occurring soon after the first flush of water in the early Wet season (figure 11) (Humphrey & Simpson 1985). This second peak in condition appears to be such a flood pulse response.

If this nutrient pulse can be shown to be important for the function of Australian floodplain wetlands then it has implications for the construction of ponded pastures, a controversial issue in Queensland at present, and for adequate provision of environmental flows where river regulation for irrigation occurs (almost everywhere).

A chemical budget for nutrients, nitrogen and phosphorus, entering and leaving the Magela floodplain (Hart et al 1987b) suggested that the floodplain acted as a net sink for these nutrients entering from the catchment. However, a similar budget for metals (Finlayson 1994) showed that the floodplain probably acts as a net source of major ions (sodium, potassium, calcium and magnesium) and a net sink for trace metals (figure 12). Thus, there is an indication of net export of material from the Magela floodplain to the main channel of the East Alligator River estuary; the vast herbaceous swamps do not simply function as a sponge soaking up nutrients washed in and filtering out particulate matter. However, none of these studies considered transport of nutrients by migratory fauna. Up-stream migration for spawning by salmon and other fish species has been shown to be a major source of nutrients for the aquatic community in Northern Hemisphere rivers. It could also be a significant pathway in other river systems.

4.5 Energy flux and food webs

The ecological energetics of tropical freshwater wetlands in Australia has received little attention until recently. Much work has been done on mangrove swamps in north Queensland, however. Dietary studies of vertebrates provide some idea of energy pathways at the higher consumer levels but little work has been done on the invertebrates which comprise much of the lower parts of the consumer food chain (figure 13) (Bishop & Forbes 1991). An interesting feature among the freshwater fish is a high incidence of omnivorous species that are rare in temperate waters.

The characterisation of trophic and nutrient processes in tropical wetlands remains a challenge. Fundamental to the management of natural ecosystems is knowledge of what are the major carbon sources that 'drive' it. In rivers and streams knowledge of the relative importance of inputs autochthonous sources (algae and macrophytes) and allochthonous sources (terrestrial detritus and fauna) has important implications for land-use management, especially of the riparian zone. Where autochthonous primary production is important (most lentic wetlands and many streams) the role of algae and macrophytes in food webs needs clarification. Whilst there are many planktonic and benthic invertebrates that 'graze' on algae there are very few that directly consume macrophytes. Until recently, macrophytes were assumed to enter the food web after death as detritus and this material was thought to flow through food chains via decomposers and detritivores. However, carbon and nitrogen isotope studies that trace carbon sources have shown that for some swamp grasses this detrital pathway to higher level consumers may not exist. In these cases the trophic function of the grasses may be to simply provide a substrate near the water surface for periphytic algae to grow on. This information has implications for evaluating management practices such grazing and the ecological impact of weed species. Some work along these lines has been undertaken in north Queensland (Bunn et al 1997). Isotope studies are also part of a current study of the impact of paragrass on the Magela Creek floodplain in the NT.

Where a range of different types of wetland are inter-connected, it may also be very important to examine the exchange of energy/carbon and nutrients between the different sections of the wetland system. This occurs largely by passive stream transport (nutrients as dissolved and suspended solids, detritus, algae and invertebrates). However, there may also be significant active transport by the migration of fish and birds. Both processes, but particularly the latter, can be seriously affected by human activities. Consequently, knowledge of its presence and ecological significance is important for planning purposes.

5 Biogeography of fauna and flora

Coastal wetlands can wax and wane rapidly with changes in climate and many of their inhabitants are, of necessity, highly vagile species that are widespread. Also, the freshwater wetlands of the Northern Territory's coastal floodplains are very young (2–3000 y) (Woodroffe et al 1985). Hence it is unlikely that these wetlands would contain many specialised endemic biota. Sediments of the seasonally-flowing portions of the streams in the lowlands are comprised of unstable, shifting sands and are also relatively young (<6000 y) as the result of infilling of deep (10 m) Holocene channels (Roberts 1991). In contrast, the Arnhemland escarpment is very ancient (Mesozoic). The permanent streams associated with the sandstone massif and outliers are, therefore, likely to have been present for a very long time so that endemic elements in their biota may be present, either as relict species or through local speciation. Consequently, these areas should be targeted in future survey and monitoring work where conservation of biodiversity is the management target.

The possibility of endemism is supported by the freshwater fish. Two freshwater fish species (Mariana's hardyhead *Craterocephalus marianae* and the black anal-fin grunter *Pingala midgleyi*) have a very restricted distribution, occurring only in the headwaters and lowland streams of the ARR and nearby western Arnhemland, and appear to be associated with the sandy substrates derived from the sandstone plateau. Also, several fish species (*Melanotaenia exquisita, M. trifasciata, Toxotes lorentzi* and *Hephaestus carbo*) have a very disjunct occurrence among the permanent escarpment streams (Bishop & Forbes 1991, Larson & Martin 1990) indicating that quite strong isolating mechanisms may occur, even among streams on the same river system. In contrast, most fish species in the floodplain zone are relatively widespread species.

The absence of exotic species of freshwater fish in the ARR is worthy of mention, as it is an increasingly rare situation on a national and global scale.

The biogeographic situation for invertebrates is not well known. However, there are several, described and undescribed, species of macrocrustaceans inhabiting permanent escarpment waters for which there are only one or a few site records at this stage (Humphrey & Dostine 1994).

5.1 Latitudinal and other spatial effects on taxa richness

One of the most accepted patterns in ecology is the increase in species diversity from the poles to the tropics. Most frequent explanations for this pattern invoke concepts of climatic stability, geological age, habitat heterogeneity, high productivity, predator-prey relationships, and comparative interactions (Shiel & Williams 1990). When these authors examined this pattern for different groups of freshwater biota on the Australian continent, different patterns were observed. Species richness is generally depressed in zooplankton and littoral microfaunal species in the tropics; for fish and macroinvertebrates tropical species richness is either higher or not lower than for comparable temperate systems; the situation for algae and macrophytes is unknown. This situation casts doubt on the value of this pattern as a useful construct for management planning. This is probably largely a result of inadequate knowledge at present and it may be a useful question to readdress in the future.

Bishop & Forbes (1991) made some interesting analyses of species-area relationships that relate to this question. They found that, although the total freshwater fish fauna of Australia is very species poor for a continent of this size, when the Australian tropical streams are compared with relationships for floodplain rivers on other continents they have as many or more species (figure 14). Also, in relation to the size of the catchment, tropical streams in Australia contain more species than temperate streams. More recently Pusey & Kennard (1996) demonstrated that, over a much smaller latitudinal range, a latitudinal change in the species-catchment area relationship occurs in coastal streams in north Queensland (figure 15).

In the Northern Territory, water softness, seasonality of flow, recency of ecosystem formation and lack of significant habitat heterogeneity (especially vast tracts of sand substrate and lack of altitudinal gradients) mitigate against significant speciation in many freshwater invertebrate groups.

6 Life history strategies

6.1 Breeding cycles

The reproductive cycle of most vertebrate species in the Wet-Dry tropics is timed to take advantage of seasonal abundance of resources offered by the Wet season. Thus the gonads of most fish species mature at the end of the Dry season in readiness for spawning when the rains come and provide a vast increase in available habitat for them and their progeny. A few species, rainbowfish and hardyheads, appear to spawn to some extent year round. Food resources for waterbirds are most abundant later in the Wet season and breeding occurs from the mid-Wet to early-Dry seasons, depending on seasonal rainfall, when floodplain grasses start seeding. Saltwater crocodiles start nesting early in the Wet season. Freshwater crocodiles and turtles, however, reproduce in the Dry season, presumably to avoid flooding of their buried eggs.

The reproductive strategies of invertebrates are no doubt extremely varied. Many have short and continuous breeding cycles and seasonal flooding provides opportunities for extensive colonisation and high production in lowland waterbodies. The familiar mass emergence of dragonflies at the end of the Wet season is not necessarily an indication of a general pattern. For example, the cherubin (*Macrobrachium rosenbergi*), a very large prawn, migrates to sea during the early–mid Wet season for spawning and their small progeny migrate upstream towards the end of the Wet season.

6.2 Survival strategies

For the aquatic biota of highly seasonal habitats, strategies have evolved for taking advantage of the seasonally-available resources in the Wet season and persistence through harsh Dry season conditions. Many plants, and some invertebrates, remain on site in the dry sediments as desiccation-resistant and/or dormant stages of the life cycle. However, some species die out in these areas and recolonise them by stream or aerial transport from populations surviving the Dry season in permanent habitats (Paltridge 1992). The strategy used by birds (Morton & Brennan 1991), fish (Bishop & Forbes 1991), and possibly some reptiles (such as filesnakes and crocodiles), is to undertake a regular migration of some form between seasonal and permanent water habitats (figure 16).

Fish migration between the floodplain and lowland stream channels of Magela Creek has been studied for 10 years by ***eriss*** as a potential method for detecting effects of mining (Bishop et al 1995, Pidgeon et al in press). Rainbowfish (*Melanotaenia splendida inornata*) and perchlets (*Ambassis* spp.) comprise over 90% of the migrants. The upstream migration of these species is much (at least 9 times) greater than the downstream migration (Pidgeon & Boyden 1993). As well as being a potential survival strategy for reaching permanent upstream habitats, this migration represents a significant net transfer of energy from the floodplain systems to the lowland/headwater sections of streams. On several days during the 1995 Wet season, it was estimated that there was 0.5–1.0 tonnes (wet weight)/day of rainbowfish leaving the floodplain; these fish would contribute substantially to the diet of upstream predators. This information should be of relevance to environmental managers planning the construction of any in-stream or riverbank structures. Further information on movements of other fish species between seasonal floodplain swamps and permanent billabongs would be useful for evaluating land-use practices and fisheries management.

In seasonal stream channels, most macroinvertebrates die out during the dry phase and recolonise the stream by downstream drift from permanent headwaters (Paltridge et al 1992). Information on the survival strategies used by invertebrates in seasonal floodplain habitats is needed and is currently being examined by staff at ***eriss***.

It is clearly important for conservation management to have some understanding of these survival strategies. The most intensively studied wetland animal species in the Wet-dry tropics are the economically important barramundi (*Lates calcarifer*), saltwater crocodile (*Crocodylus porosus*) and magpie goose (*Anseranas semipalmata*) (Bayliss & Yeomans 1990, Morton et al 1990, Griffin 1995, Webb et al 1987). The migratory movements and population dynamics of these species are quite well understood and management strategies are in place to ensure their sustainable harvesting and conservation. Whilst other species are not exploited to the same extent, similar information on many other species would be useful to provide an ecological basis for reserve design and management.

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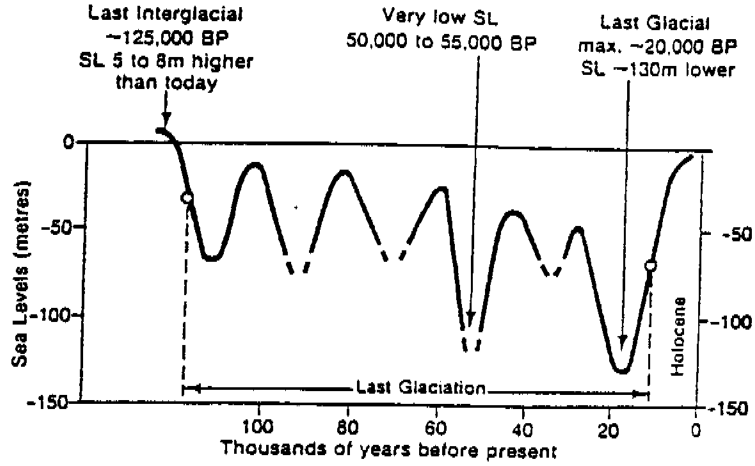


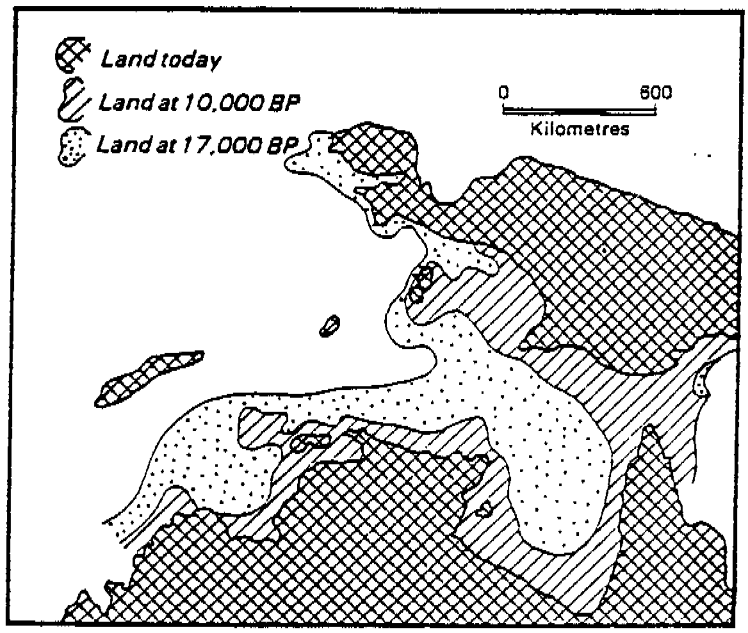


Figure 5. Sea level fluctuations during the past 125,000 years, and some associated changes in the coastline of northern Australia and Papua New Guinea, slightly modified from Chappell (1976, Figures 1 and 3).

Fig. 1. Sea level and coastline changes in northern Australia over the last 125,000 years.

from Williams (1991)

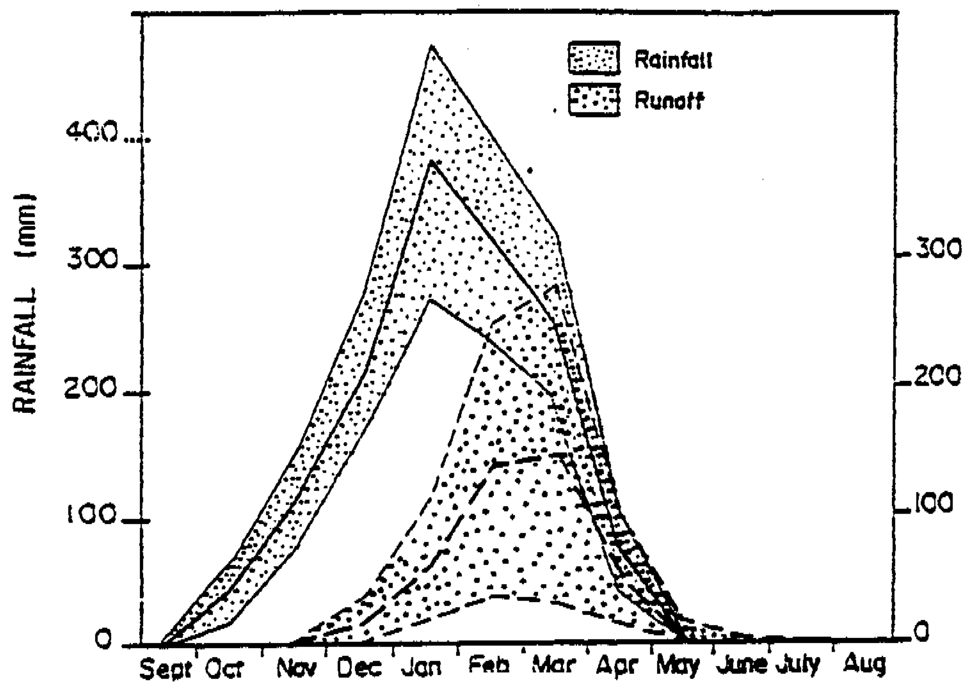


Fig. 2 Runoff and incidence in the Adelaide River basin in relation to rainfall (rainfall for Darwin; runoff regionalised for 6 stations in the Adelaide River basin; zones show range from 30% to 70% probability of occurrence). From Williams (1991)

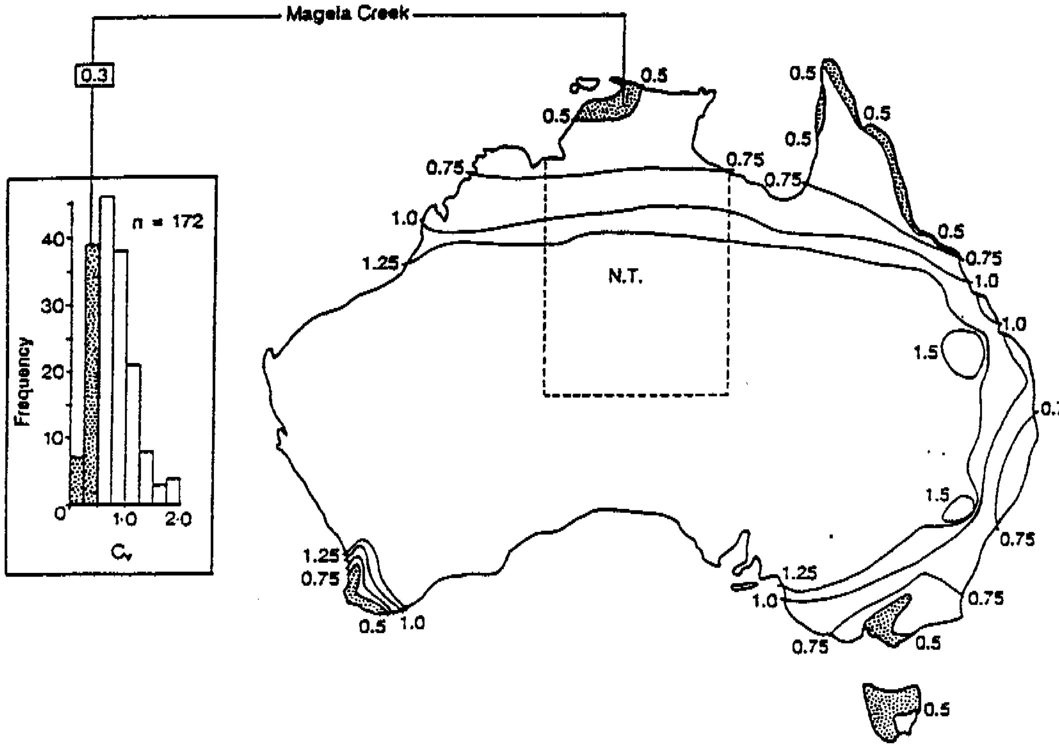


Fig. 3. Map of Australia showing contours of coefficients of variation (C_v) of annual discharge of rivers. Drawn after McMahon (1979) who examined hydrological data from 172 rivers (see frequency histogram of C_vs for these rivers to the left). The Northern Territory (N.T.) contours have been modified following data supplied by the N.T. Water Division. Stippled areas have C_v < 0.5.

Fig. 3. Variability of river discharge in different areas of Australia.

from Humphrey et al (1990)

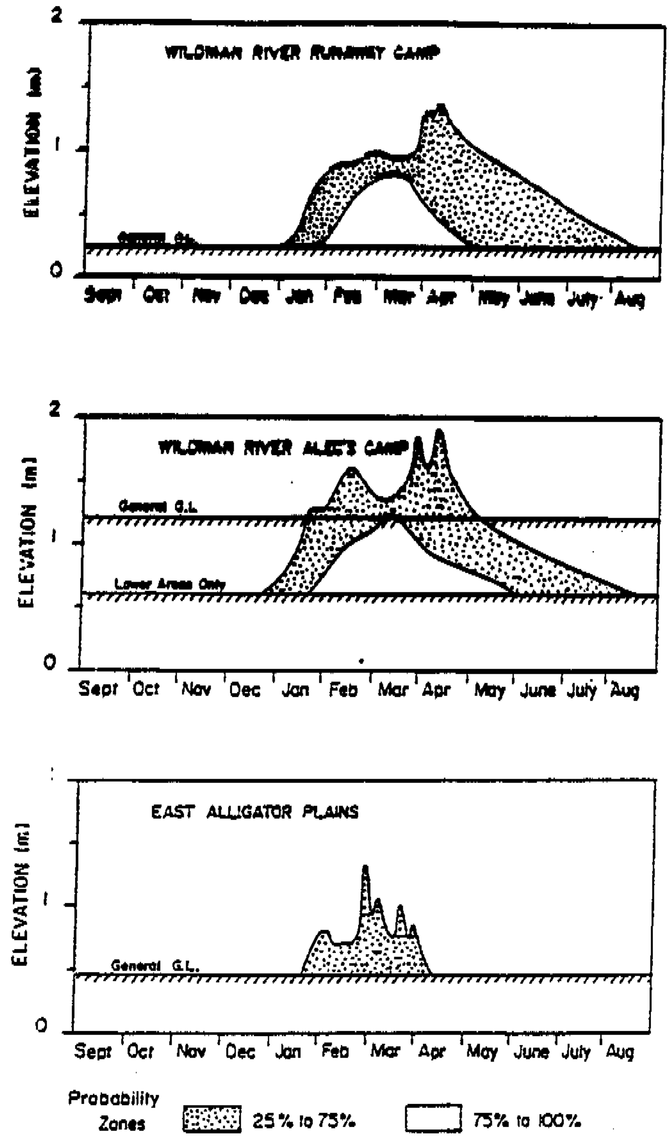


Figure 25. Flooding probability in the Wildman and East Alligator basins (after Purich 1965).

Fig. 4 Seasonal inundation patterns on different floodplains showing spatial and temporal variation

from Kingston (1991)

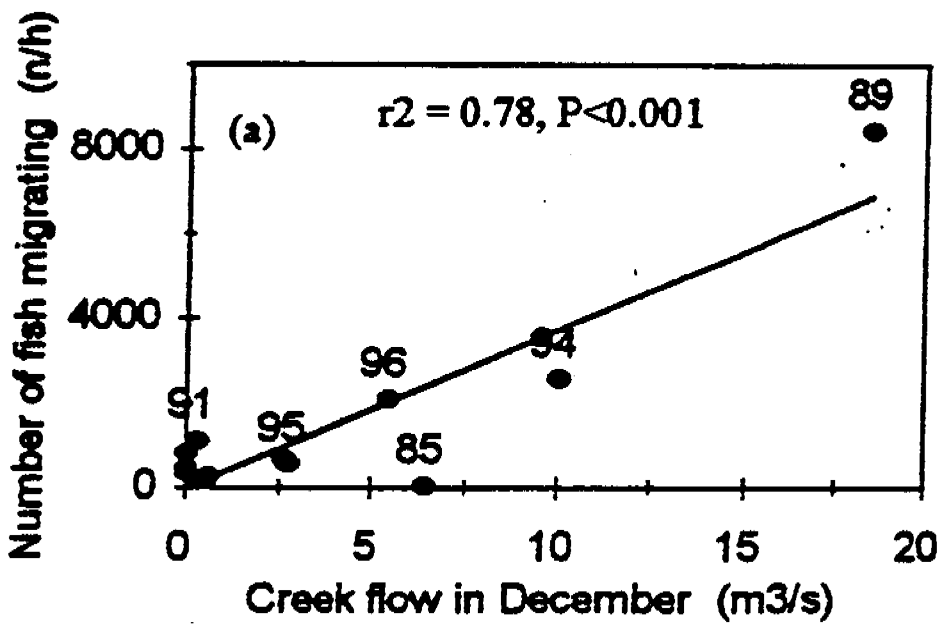


Fig. 5. Annual mean migration rate of chequered rainbowfish (*Melanotaenia splendida inornata*) in Magela Creek in relation to the discharge in the first month of flow, December.

symbol numbers indicate years

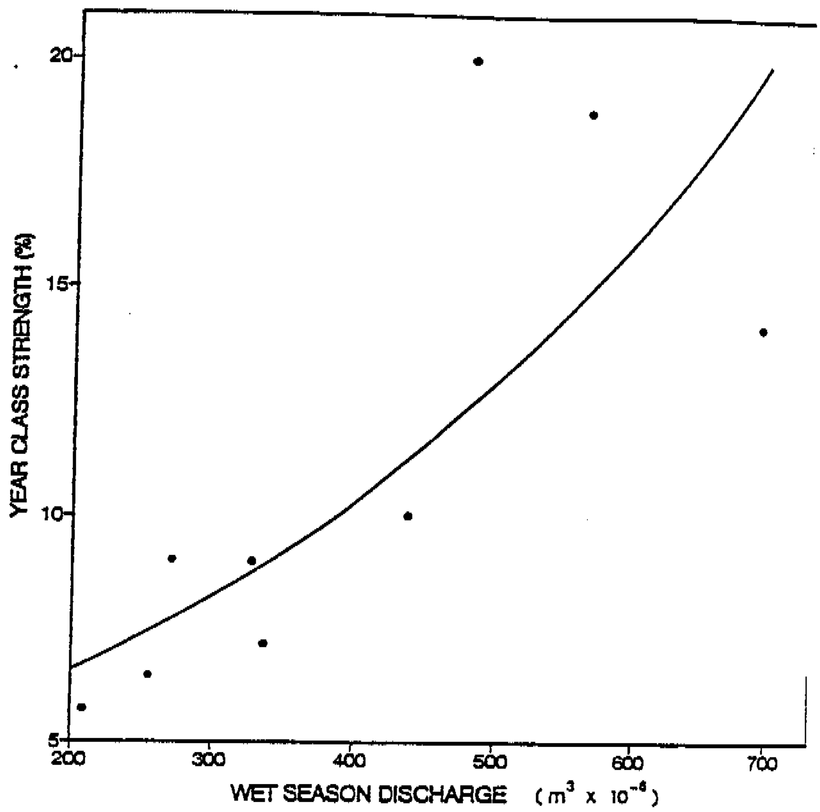


Fig. 6. Exponential relationship between year class strength of mussels (Velesunio angasi) in the floodplain billabongs of Magela Creek, NT, and Wet season discharge.
from Humphrey (1984)

Table 5. Temporal variability of stream macroinvertebrate communities across different regions of Australia, based upon family-level, presence-absence data. (See text for explanation of inconstancy indices.)

Region	Flow status	Inconstancy index (%dissim> 0.35)	Inconstancy index (mean threshold)	Inconstancy index (mean dissimilarity)	CV of annual flow	Latitude (°; decimal minutes)	Comments on persistence and mechanism for relative lack of persistence
Temperate (VIC-Latrobe)	Permanent	4.5	1.1	0.266	0.32	38.0	High persistence (to some degree an artefact of combine seasons and habitat data).
Temperate (SW WA)	Permanent	6.5	1.6	0.244	0.49-0.73	32.3	High persistence (predictable pattern of flow)
Temperate (TAS)	Permanent	7.5	1.9	0.204	0.47	41.3	High persistence (predictable pattern of flow)
Wet-dry tropical (SAR, NT)	Permanent	13.5	4.0	0.234	0.58	13.35	High persistence (predictable pattern of flow)
Wet tropical (NE QLD)	Permanent	15.0	6.3	0.256	0.5	18.1	High late dry season persistence; cause of low early dry season persistence unknown (cyclonic disturbance/opening of canopy in early 1990s?)
Wet-dry tropical (RMC, NT)	Seasonal	17.0	4.3	0.237	0.58	13.35	Lower taxa richness in 1992 associated with low wet season rains and discharge
Subtropical (SE QLD)	Permanent	19.0	13.0	0.293	1.04-1.07	26.3	High autumn persistence; low persistence in spring associated with drought (1995
Temperate-dry (VIC-Wimmera)	Seasonal	19.5	8.3	0.257	0.58-0.98	36.3	Seasonal flow (pools in dry season)
Wet-dry tropical (Magela, NT)	Seasonal	21.0	9.8	0.279	0.56	12.4	Seasonal flow (little or no surface water by end of dry season)
Temperate (SW WA)	Seasonal	24.0	11.4	0.264	0.49-0.73	32.3	Seasonal flow (little or no surface water by end of summer 'dry season')
Temp. semi-arid (Flinders, SA)	Permanent (riffle)	25.0	8.3	0.290	1.25	31.1	Reasonably high persistence (sites of permanent flow)
Sub-alpine (NSW)	Permanent	27.5	12.3	0.268	0.5-0.75	36.3	High summer persistence; low persistence in spring associated with snow-melt floods (eg 1992).
Temp. semi-arid (Flinders, SA)	Permanent (macro, pool)	51.7	30.9	0.387	1.25	31.1	Low persistence of pool and macrophtye fauna compared with that in riffles. 'Flashiness', and occasional severe floods characteristic of these streams may affect fauna of the habitats differently.
Dry tropics (Pilbara, WA)	Seasonal	93.0	60.0	0.431	1.4	21.3	

Fig. 7. Persistence of stream macroinvertebrate communities across different bioregions of Australia. After Humphrey et al (1997).

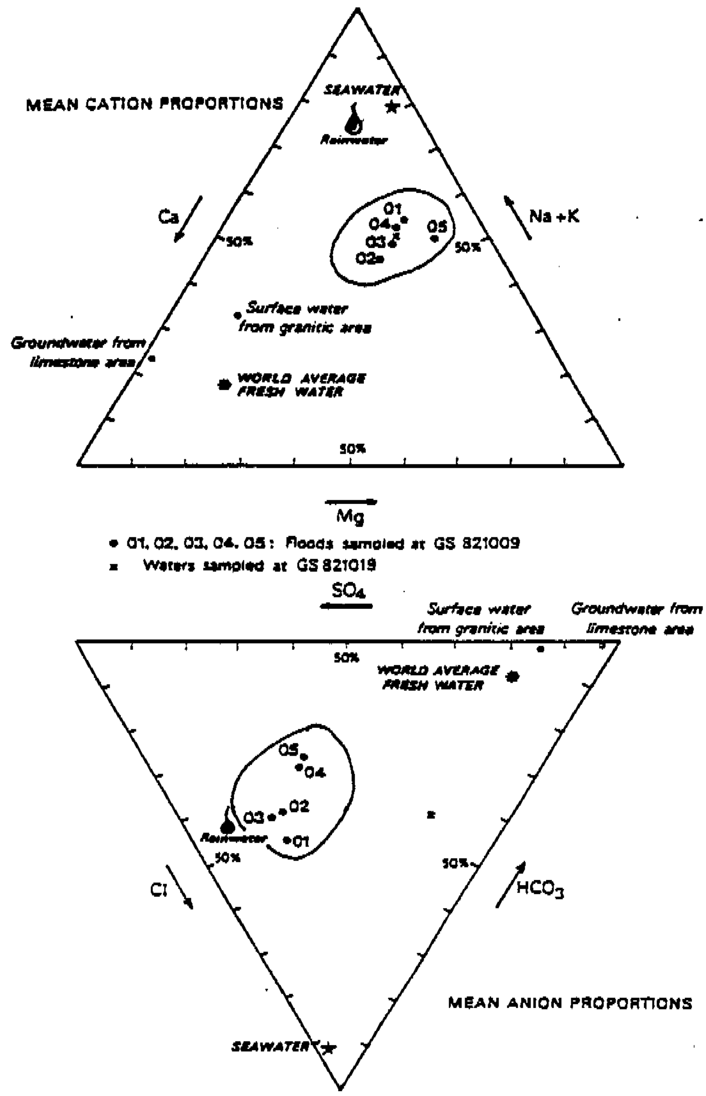


Fig. 5. Relative ionic composition of Magela Creek water (flood events 01–05) and rainwater, both collected at GS821009. For comparison, ionic composition of seawater, 'world average fresh water', and two different fresh waters are also shown.

Fig. 8. Chemical composition of magela Creek water in comparison to local rainwater, world average freshwater and seawater.

from Hart et al. (1987)

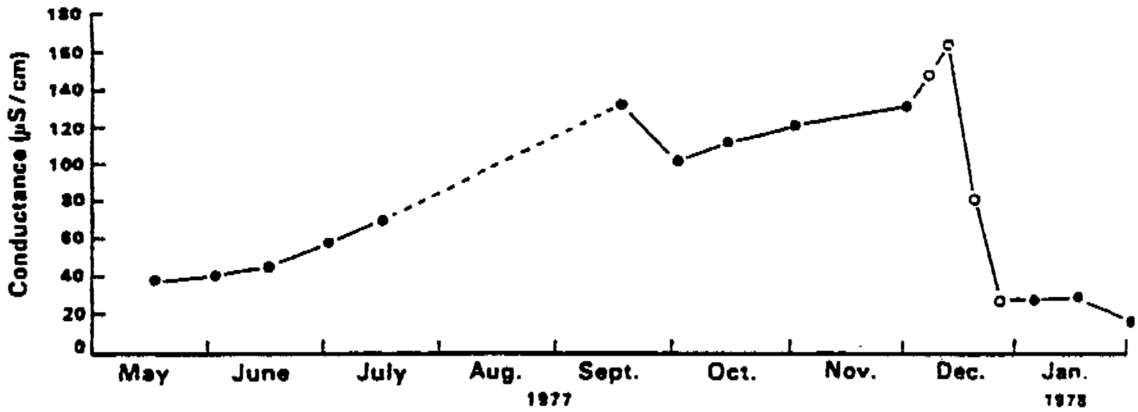


Fig. 3. Conductivity in Jabiluka billabong from May 1977 to February 1978. Data obtained from Water Division, Northern Territory Department of Transport and Works (●) and this study (○).

Fig. 9. Seasonal change in conductivity of floodplain billabong water

from Hart and MacGregor (1980)

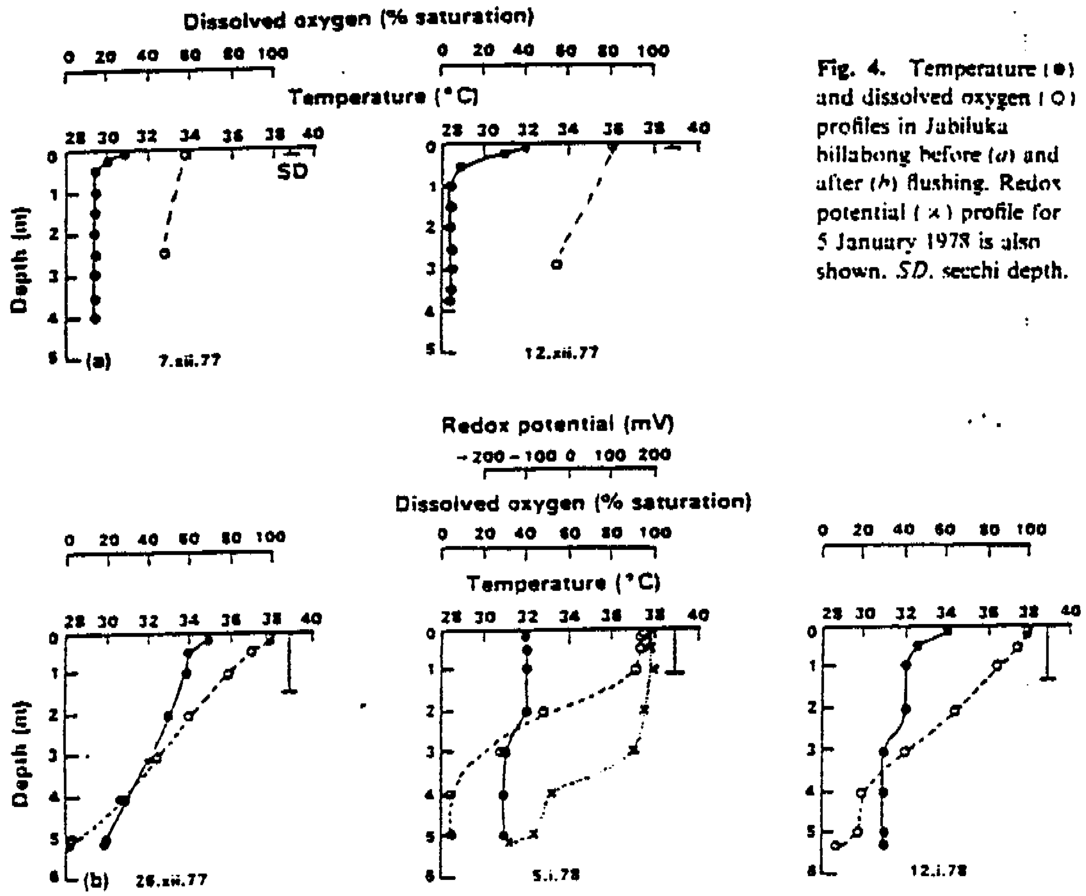


Fig. 10 Temperature and oxygen depth profiles in Jabiluka Billabong before (December) and after (January) the first flush of Wet season water.

from Hart and MacGregor (1980)

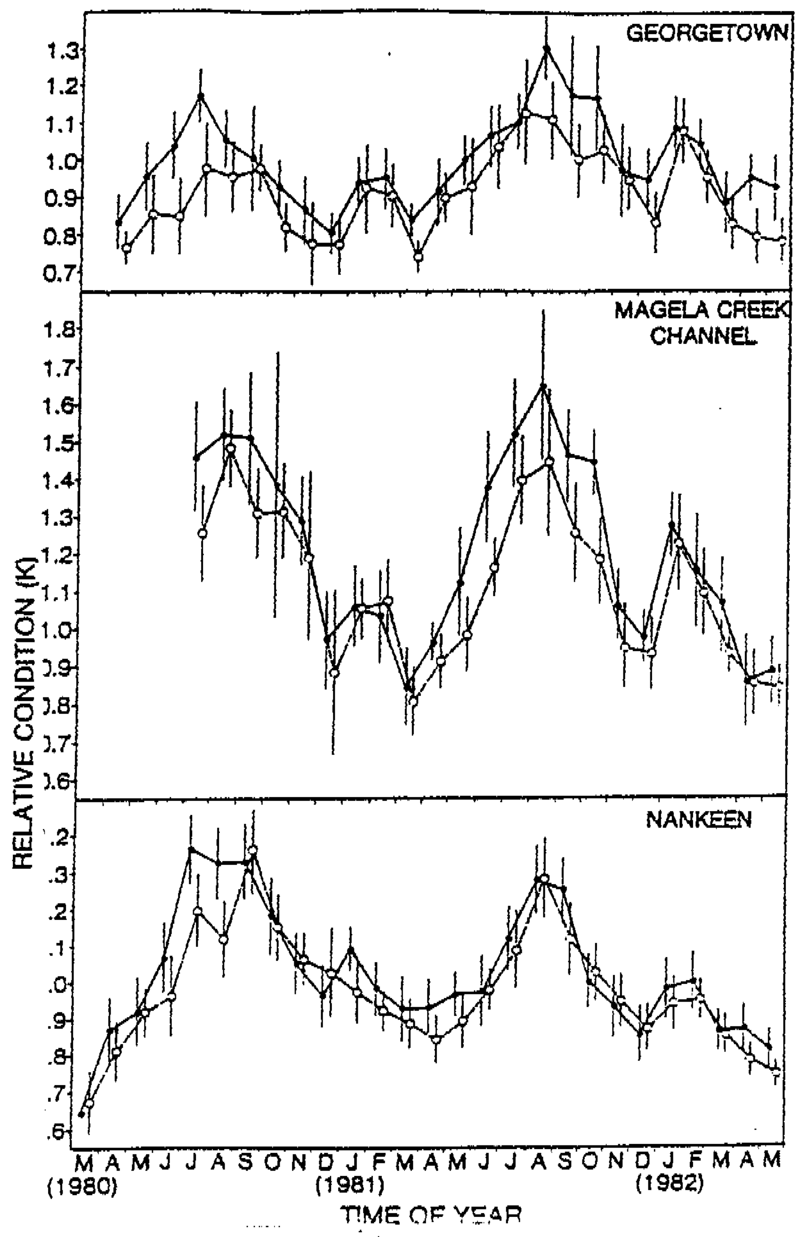


Fig. 11. Mean relative condition (K) of male (solid circles) and female (open circles) mussels (Velesunio angasi) in selected waterbodies of Magela Creek, NT. 95% confidence limits are indicated by vertical lines.

Figure is from Humphrey (1984).

Table 13.2. Calculation of material loads entering and transported from the Magela floodplain during the 1982–1983 wet season. Error estimates are given in brackets. See Hart *et al.* (1987) for sampling methods and the estimation of errors

	Material load of			
	Runoff	Rainfall	Output	Net load
Sodium (t)	370 (90)	33 (13)	630 (150)	−220 (180)
Potassium (t)	120 (50)	13 (16)	200 (55)	−60 (75)
Calcium (t)	120 (150)	4 (11)	310 (72)	−180 (170)
Magnesium (t)	170 (46)	4 (7)	390 (110)	−220 (120)
Iron (t)	230 (230)	[a]	680 (190)	−450 (300)
Manganese (t)	6 (3)	1 (1)	2 (1)	+4 (3)
Copper (kg)	410 (610)	89 (50)	65 (35)	+440 (610)
Lead (kg)	83 (35)	67 (65)	22 (12)	+130 (75)
Zinc (kg)	250 (250)	910 (930)	87 (47)	+1100 (970)
Uranium (kg)	42 (240)	18 (9)	11 (6)	+48 (240)

[a] Missing value.

Fig. 12. Chemical budget for the floodplain basin of Magela Creek, NT.

From Finlayson (1994).

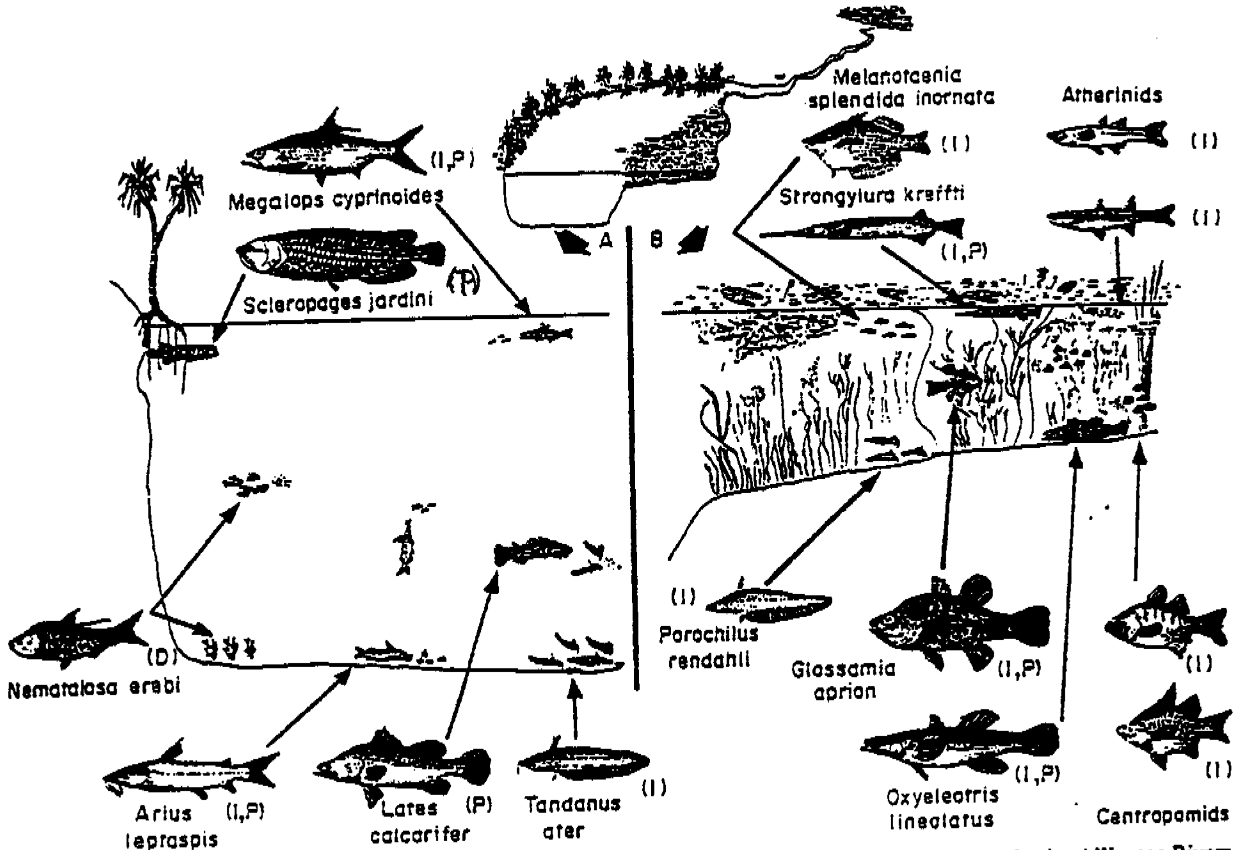
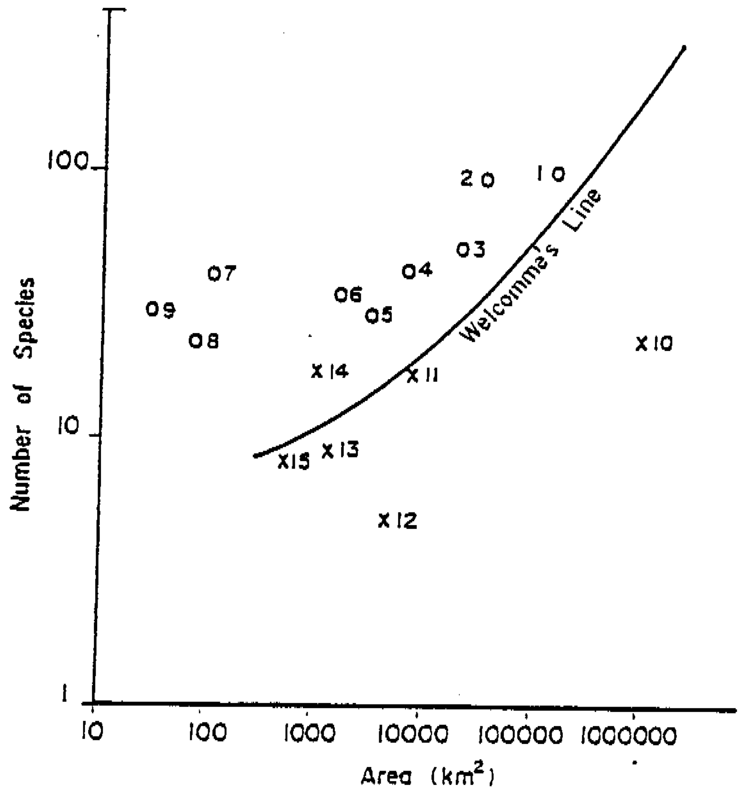


Figure 45. Feeding habits of fishes in deepwater (A) and littoral zones (B) of floodplain billabongs in the Alligator Rivers region. Invertebrates are consumed by many small fish species (I) in the littoral zone and by larger species (I) in the deepwater zone. The smaller fish are in turn consumed by piscivores (P) within the littoral zone and the deepwater zone. A few species (D) consume detritus and phytoplankton in the deepwater zone.

Fig 13. A simpistic food web for fish in Top End billabongs.

From Bishop and Forbes (1991)



Tropical:O			Temperate:X		
Code	System	Source	Code	System	Source
1	Fly R.	Roberts (1978)	9	Baroalba Ck.	Bishop & Harland (1981)
2	Purari R.	Haines (1979)	10	Murray-Darling	Lake (1979)
3	Alligator Rvs.	Bishop *et al* (1982)	11	Shoalhaven R.	Bishop (1979)
4	Laloki R.	Berra *et al* (1975)	12	Ironstone Ck.	Lake (1982)
5	Jardine R.	Allen & Hoese (1980)	13	Parson's Ck.	Lake (1982)
6	Magela Ck.	Bishop *et al* (1982)	14	Tweed R.	Richardson (1984)
7	Black-Alice R.	Buemer (1980)	15	Seven Creeks	Cadwallader (1979)
8	Gulungul Ck.	Bishop & Harland (1981)			

Fig. 14. Relationship between catchment area and number of fish species for Australian rivers compared to the relationship indicated by Welcomme's line based on 45 rivers on other continent

from Bishop and Forbes (1991)

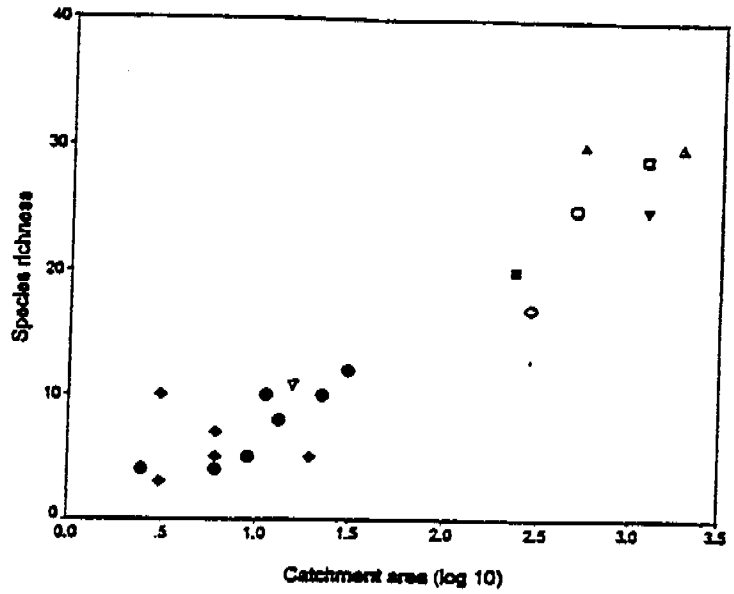


Fig. 2. The relationship between catchment area (km^2, log transformed) and fish species richness. Drainage basins are distinguished by the following symbols: ○, Bloomfield River; ●, Cape Tribulation area; □, Daintree River; ■, Mossman River; △, Barron River; ▲, Russell River; ▽, North Hull River; ▼, Tully River; ◇, Murray River; ◆, Cardwell area.

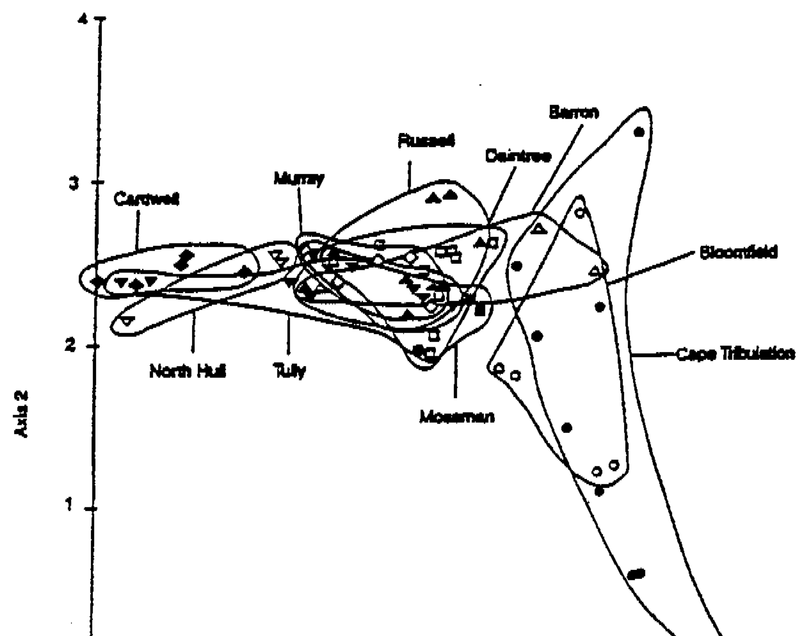


Fig. 4. The distribution of study sites in ordination space as defined by DECORANA Axes 1 and 2 of an ordination of weighted species abundance data from which all sites located above major discontinuities in river profile were omitted. Drainage basins are distinguished by the same symbols as in Fig. 2.

Fig. 15. Relationship between (a) fish species richness and catchment area and (b) fish community structure and latitude for coastal rivers in northern Queensland

from Pusey and Kennard (1996)

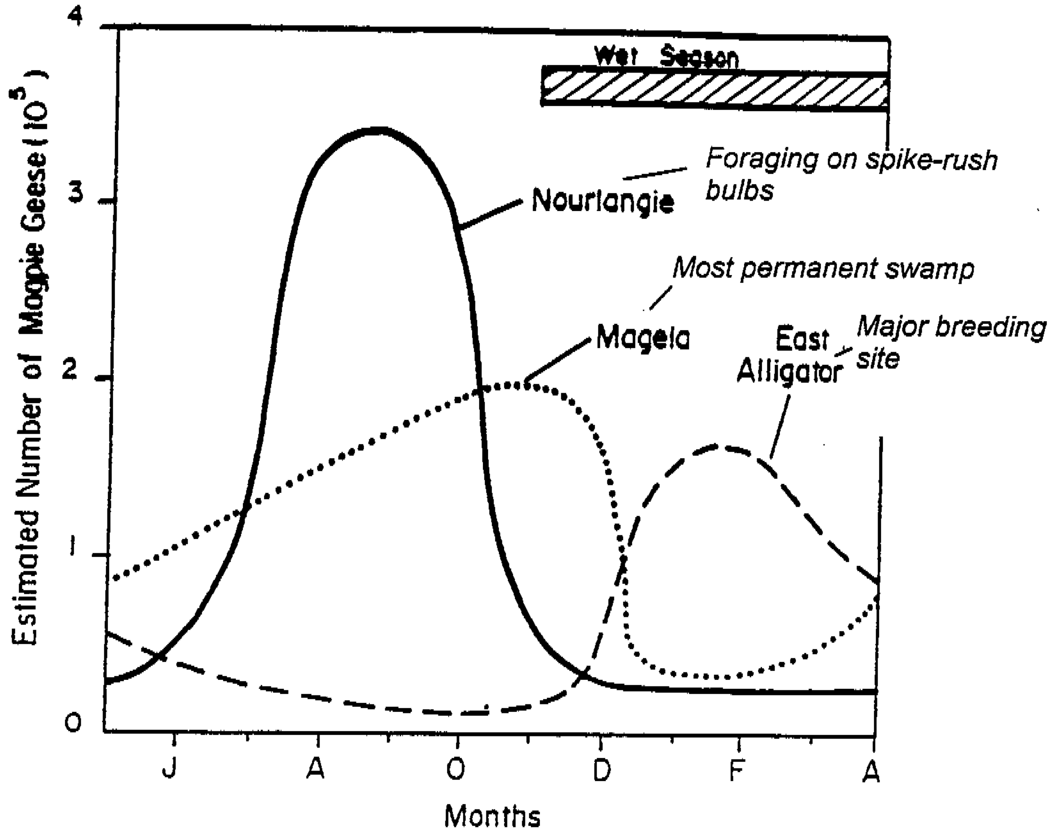


Figure 53. Seasonal changes in the numbers of Magpie Geese occurring on three floodplains in the Alligator Rivers region. The estimates are based on aerial surveys during 1981-1984 (S.R.Morton, K.G.Brennan & M.D.Armstrong, unpubl. data).

Fig. 16 Seasonal pattern of usage of different wetland habitats by magpie geese.

from Morton and Brennan (1991)

Wetland classification and inventory in northern Australia

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Abstract

Wetland classification is still the subject of debate in Australia with several national programs using different systems. The classification systems used for an overview of Australian wetlands and the LWRRDC scoping review of Australian wetlands, and that used for the directory of important wetlands are described. These are compared with a recently prepared geomorphic-based system of classification. An inventory of Australian wetlands does not exist, although an overview was provided in the 1980s as part of a national program. The recent directory of important Australian wetlands has compiled much of the existing information base and led to moves to consider a process for developing a national wetland inventory. Currently, the status of wetland inventory information in northern Australia is uneven and incomplete.

Keywords: Australian wetlands, classification, inventory, Directory of Important Wetlands

1 Introduction

A comprehensive inventory of the wetlands of northern Australia does not exist (Finlayson et al 1997, Storrs & Finlayson 1997), although it is much further advanced in Queensland (Blackman et al 1992, 1993, 1996) than in Western Australia (Lane et al 1996) or the Northern Territory (Whitehead & Chatto 1996). The recently compiled Directory of Important Wetlands in Australia (ANCA 1996) provides an invaluable description of the inventory information held by governmental agencies, but it is not intended as a comprehensive inventory. It does, however, provide the basis of a systematic collation of information on wetlands and could lead to the development of a national inventory. Thus, it could lead to a national inventory with active processes in place to obtain further information and be regularly updated.

A recent recommendation from the ANZECC Wetlands Network (encompassing representatives from all state/territory conservation agencies and several federal bodies) supports this intention. Under the auspices of the federally funded National Wetlands Program the Environmental Research Institute of the Supervising Scientist has been asked to liaise with appropriate agencies to develop a draft proposal for a national wetlands inventory. These moves are encouraging and could lead to a greatly enhanced information base for wetlands in northern Australia. The importance of a comprehensive wetland information base has been promoted by the Ramsar Wetland Convention and various wetland conservation fora (Dugan 1990, Blackman et al 1992, Finlayson 1996).

The extent of existing wetland classifications and inventory effort in northern Australia is outlined below, with a particular emphasis on national approaches. Hence, the classification systems used by Paijmans et al (1985) and ANCA (1996) are described along with the newly promoted approach of Semeniuk & Semeniuk (1995, 1997). The 'inventories' described are the national directory project (ANCA 1996) and the overview provided by Paijmans et al (1985) which was used as the basis for the LWRRDC scoping review of R&D for wetlands (Bunn et al 1997).

2 Classification

Finlayson & von Oertzen (1993) reported five wetland classification systems that had been used in northern Australia. In addition, ANCA (1996) proposed a further system for the Directory of Important Wetlands in Australia, and Semeniuk & Semeniuk (1995, 1997) have proposed a completely different approach using geomorphic features. Given their current status the latter two systems are briefly described along with the Paijmans et al (1985) system for a generalised overview of Australian wetlands. Unfortunately there is no general acceptance of one or the other of these systems. For example, the National Wetland Program is supported by both LWRRDC and the Biodiversity Group of Environment Australia (encompassing ANCA), but both have adopted different classification systems. The difficulties with applying the classifications have also led Storrs & Finlayson (1997) and Finlayson et al (1997) to adopt a much simplified, but not accurate (*sensu* Semeniuk & Semeniuk 1995, 1997), set of wetland categories for northern Australia which is largely based on geographic location. These categories are given below.

Wetland categories in northern Australia
Coastal marshes
Mangrove swamps
Freshwater lakes and swamps
Floodplains
Freshwater ponds and swamps

The above example reinforces the case for determining and field testing a national classification of wetlands and, if needed, the inclusion of regional differences or modifiers. It is also stressed that local names for various wetland types should not be discouraged and the means of including these in the classification (eg cross referencing) should be investigated. The rationale for this is based principally on the need to encourage local association with the classification, and hence its use; foreign names may do little to promote ownership of the classification.

2.1 Generalised overview of Australian wetlands

Paijmans et al (1985) adopted a loosely defined classification that was lacking in detail compared to the system developed by the United States Fish and Wildlife Service (Cowardin et al 1979). The latter was not adopted as it was regarded as too detailed for use in Australia where many wetlands lacked detailed descriptions. Whilst recognising these issues Paijmans et al (1985) acknowledged that problems of gradation between wetland types, lack of seasonal information, and inconsistent and indefinite terms still had not been fully resolved in the system they proposed. Finlayson & von Oertzen (1993) also point out that in northern Australia the degree of permanence and salinity of many inland lakes also needed further consideration.

The classification system adopted was simple and loosely hierarchical with categories, classes and sub-classes (table 1) based on hydrologic and vegetation characteristics. There are six categories – lakes, swamps, land subject to inundation, rivers and creeks, tidal flats, and coastal inshore waters. As a rule these were fairly identifiable on topographic maps although there was some confusion between swamps and land subject to inundation. The key features of the six categories are given below.

Wetland category	Hydrologic and/or vegetation features
Lakes	Open water bodies generally more than 1m deep when full Permanent emergent vegetation, when present, is confined to the margins Differences between classes of lakes are not clear-cut
Swamps	Generally less than 1 m deep when full Dominated by emergent vegetation
Land subject to inundation	Seasonally or intermittently flooded but not usually long enough for hydrophytic vegetation to develop Terrestrial vegetation can be common
River and creek channels	Channels for the conveyance of surface runoff Many intergrades between the classes recognised
Tidal flats	Areas subject to tidal inundation at least once per year Frequency and nature of inundation varies from daily by high tides to rarely and associated with freshwater flooding
Coastal water bodies	Water bodies with varying degree of access to the open sea

The classes used in this classification are based on permanency of water and frequency of flooding (table 1). Thus they reflect the hydrologic, climatic and tidal features of the region. The sub-classes reflect the geologic and geomorphic context and location in the hydrologic basin. As such they tend to be rather *ad hoc* and many others could be added if more detailed landscape information was available.

2.2 Directory of important wetlands in Australia

The classification system adopted for the Directory is based on that used by the Ramsar Wetland Convention (Scott & Jones 1995) which was in turn modelled on the hierarchical system used in the USA (Cowardin et al 1979, Wilen & Bates 1995). The latter is divided into systems, sub-systems, classes and sub-classes (table 2) together with a series of modifiers concerning water regime, water chemistry (salinity, pH) and soil. The basic unit of the hierarchy is the 'system', of which five are distinguished (table 2). After being in use for more than a decade Cowardin & Golet (1995) reviewed the USA system, and despite recommending some changes were generally happy that it had served a useful purpose. The Ramsar Convention classification (table 3) is simpler than that used in the USA with three systems – marine and coastal, inland and human-made (Scott & Jones 1995).

The classification used in the Australian Directory is shown in table 4. It uses the same three hierarchical 'systems' as that used in the Ramsar Convention classification. To reflect the Australian situation three further wetland types were added – non-tidal forested wetlands, rock pools, and karst systems. In 1996 subterranean karst systems were included in the Ramsar classification after representation from Australia. A similar classification was developed for Queensland as the basis of a state-wide wetland inventory (Blackman et al 1992).

2.3 Geomorphic classification of Australian wetlands

A global approach to wetland classification combining attributes of landform setting and hydroperiod was proposed by Semeniuk & Semeniuk (1995). The categories of landform and hydroperiod used in this classification are given below.

Landform setting categories	Hydroperiod (water availability) categories
Basins	Permanently inundated
Channels	Seasonally inundated
Flats	Intermittently inundated
Slopes	Seasonally waterlogged
Highland/Hills	

Combining the landforms and hydroperiods generates 13 wetland categories that can be further described systematically and hierarchically using descriptors to denote wetland shape and size, soils, vegetation, and water salinity and its consistency throughout the year. The system is referred to as a geomorphic one as landforms form the first stage in the hierarchy. That is, wetland geomorphic geometry is noted first and then divided further on hydroperiod. The first stages of this classification are shown in table 5.

Semeniuk & Semeniuk (1997) list four stages for the acquisition of data for the classification of wetlands. This entails progressively obtaining more detailed information on the wetlands and establishing the hierarchical separations in the classification. The descriptors within the classification allow for a rigorous, systematic discrimination of the array of wetlands. Whilst Semeniuk & Semeniuk (1995, 1997) present a set of names for the wetland types discriminated they do not encourage the abandonment of local terms, but encourage their use in parallel with a standardised globally accepted set of terms in order to facilitate further communication.

Stages for acquiring data for the classification of wetlands
• Assessment of geomorphic setting from aerial photographs
• Preliminary field survey to determine hydroperiods, soils, biota
• Field survey to determine more detailed hydroperiods, water chemistry, soils and biota
• Field survey to determine more detailed information on seasonal, and long-term dynamics

3 Inventory

Noting the above comments about the absence of comprehensive wetland inventories in northern Australia details of two recent 'inventory' approaches are given. The first is the generalised overview of Australian wetlands undertaken by Paijmans et al (1985) and the second the collation of existing information on wetlands under the national Directory of Important Wetlands in Australia (ANCA 1996).

3.1 Generalised overview of Australian wetlands

Paijmans et al (1985) record that in 1973 a proposal was put forward for a survey of the wetland habitats of Australian waterbirds and then expanded to provide information for the management and conservation of Australian wetlands. Feasibility studies were undertaken and the extent of knowledge in each state/territory assessed, but a national wetland inventory did not eventuate. Paijmans et al (1985), however, did proceed with an attempt to classify and map Australia's wetlands on a continental scale. The study was not completed, but a dyeline map of wetlands at a scale of 1:250 000 000 was prepared by analysing published 1:250 000 topographical maps.

The classification used was the same as that shown in table 1 except that all wetlands less than 1000 m across were combined as 'waterholes', seasonal and intermittent wetlands were not distinguished and combined as intermittent, flat-floored depressions more than 1000 m across that occasionally held water were classed as 'dry lake' rather than as 'episodic', and an attempt was made to distinguish between saline and non-saline wetlands. Copies of the map were made available, but were not published. The map was too large, too detailed and too inaccurate. An overview with regional descriptive information was provided (Paijmans et al 1985).

Further computer analysis of the data on the 1:250 000 000 map was made to produce frequency data for the main wetland types. An analysis of wetland assemblages was not as successful.

3.2 Directory of Important Wetlands in Australia

The Directory of Important Wetlands in Australia (ANCA 1996) has evolved from an earlier edition (Usback & James 1993) and is supported by the ANZECC Wetlands Network and the National Wetlands Program. As such, it represents the input of information on Australian wetlands as provided by governmental agencies; it does not represent the complete extent of information held by such agencies (Blackman et al 1996, Lane et al 1996, Whitehead & Chatto 1996). The inventory is coordinated by the National Wetlands Program with the state/territory agencies taking responsibility for collecting and collating the information. In this respect it does not provide an even information base given differences in the information resources and the extent to which this has been collated.

Wetlands are included in the directory on the basis of six criteria agreed by the ANZECC Wetlands Network (Phillips 1996).

Criteria for determining wetlands of national importance
• It is a good example of a wetland type occurring within a biogeographic region in Australia.
• It is a wetland which plays an important ecological or hydrological role in the natural functioning of a major wetland system/complex.
• It is a wetland which is important as the habitat for animal taxa at a vulnerable stage in their life cycles, or provides a refuge when adverse conditions such as drought prevail.
• The wetland supports 1% or more of the national populations of any native plant or animal taxa.
• The wetland supports native plant or animal taxa or communities which are considered endangered or vulnerable at the national level.
• The wetland is of outstanding historical or cultural significance.

Application of these criteria is subjective due to differences in interpretation and the extent of available information. Adoption of a biogeographical region approach has reduced the difficulty of determining whether or not a site is unique or representative, although this may not apply where these regions straddle state/territory borders.

A format for a 'minimum dataset' for describing wetlands in the Directory was also agreed (table 6). It was acknowledged that in many instances more information may be available for particular wetlands, but that this would be made available through an accompanying reference list and contact with the responsible state/territory agency. The current edition of the Directory contains information on 698 wetlands or wetland complexes of national importance. Further analysis of the information in the Directory is underway.

Information provided in the Directory covers 30 sites in the Northern Territory, with a further 19 noted in a supplementary list. Whitehead & Chatto (1996) reject the concept of relative importance of individual wetlands and strongly support the development of a comprehensive inventory of all substantial wetlands. The Queensland information base is comprehensive and covers some of the most important sites in the Gulf Plains, Wet Tropics and Cape York Peninsula bioregions of northern Australia (Blackman et al 1996). Lane et al (1996) also report a very uneven information base for wetlands in Western Australia and support moves to obtain a more systematic and even information base. A list of the wetlands of the biogeographical regions that comprise the Wet-Dry tropics was derived from the Directory by Finlayson et al (1997) and presented in table 7. The overall area of these wetlands is not accurately known but exceeds, based on available estimates, 65 000 km^2.

4 Conclusion

Wetland classification is beset with difficulties of terms and inconsistencies in attributes used to separate wetland types. There is still no agreement on the acceptance of a wetland classification system in Australia. That used for the Directory of Important Wetlands in Australia is broadly based on that developed in the USA and adapted by the Ramsar Wetland Convention. In contrast, a more general classification was used for an overview of Australian wetlands approx 15 years ago and formed the basis of a recent national review of wetland R&D needs.

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Table 1 Categories, classes and sub-classes of the hierarchical wetland classification proposed by Paijmans et al (1985)

Categories	Classes	Sub-classes
Lakes	Permanent and near-permanent	• Floodplain lakes including billabongs and waterholes in channels • Lakes of coastal dunes and beach ridge plains • Lakes in terminal drainage basins • Lakes associated with lava flows • Crater lakes • Karst lakes • Glacial lakes • Man-made lakes
	Seasonal	• Floodplain lakes • Terminal drainage basin lakes
	Intermittent	• Floodplain lakes • Coastal dune lakes • Lakes in terminal drainage depressions • Man-made lakes
	Episodic	• Lakes in terminal drainage depressions • Lakes on present or former floodplains
Swamps	Permanent	• Floodplain swamps • Swamps of coastal dunes and beach ridge plains • Swamps in terminal drainage depressions • Swamps associated with lava flows • Crater swamps • High mountain swamps • Swamps fed by springs
	Seasonal	• Floodplain swamps
	Intermittent	• Floodplain swamps • Swamps in terminal drainage depressions
	Episodic	
Land subject to inundation	Seasonal	• Floodplains • River and creek banks
	Intermittent	• Floodplains • River and creek banks
River and creek channels	Permanent and near-permanent	• Rocky • Sandy • Silty/clayey
	Seasonal	• Rocky • Sandy

		• Silty/clayey
	Intermittent	• Rocky • Sandy • Silty/clayey
	Episodic	• Rocky • Sandy • Silty/clayey
Tidal flats	Daily inundation	• Intertidal flats of open coasts • Intertidal estuarine flats • Intertidal stream banks
	Spring tidal and less frequent inundation	• Supratidal surfaces • Supratidal stream banks • Saline pools
	Spring tidal and less frequent flooding and seasonal freshwater flooding	• Supratidal flats • Brackish pools and billabongs
Coastal water bodies	Permanently open to the sea Intermittently open to the sea Rarely open to the sea	

Table 2 Hierarchy of wetlands and deepwater habitats in the wetland classification used in the USA (Cowardin et al 1979, Wilen & Bates 1995), showing systems, subsystems and classes

System	Sub-system	Class
Marine	Subtidal	• Rock bottom • Unconsolidated bottom • Aquatic bed • Reef
	Intertidal	• Aquatic bed • Reef • Rocky shore • Unconsolidated shore
Estuarine	Subtidal	• Rock bottom • Unconsolidated bottom • Aquatic bed • Reef
	Intertidal	• Aquatic bed • Reef • Stream bed • Rocky shore • Unconsolidated shore • Emergent wetland • Scrub-shrub wetland • Forested wetland
Riverine	Tidal	• Rock bottom • Unconsolidated bottom • Aquatic bed • Stream bed • Rocky shore • Unconsolidated shore • Emergent wetland
	Lower perennial	• Rock bottom • Unconsolidated bottom • Aquatic bed • Rocky shore • Unconsolidated shore • Emergent wetland
	Upper perennial	• Rock bottom • Unconsolidated bottom • Aquatic bed • Rocky shore • Unconsolidated shore

	Intermittent	• Streambed
Lacustrine	Limnetic	• Rock bottom • Unconsolidated bottom • Aquatic bed
	Littoral	• Rock bottom • Unconsolidated bottom • Aquatic bed • Rocky shore • Unconsolidated shore • Emergent wetland
Palustrine		• Rock bottom • Unconsolidated bottom • Aquatic bed • Unconsolidated shore • Moss-lichen wetland • Emergent wetland • Scrub-shrub wetland • Forested wetland

Table 3 Wetland classification used by the Ramsar Wetland Convention (Scott & Jones 1995)

Marine and Coastal	Marine	Subtidal		Shallow marine waters Marine beds Coral reefs
			Aquatic bed	
			Reef	
		Intertidal	Rocky	Rocky marine shores
			Unconsolidated bed	Sand/shingle beaches
	Estuarine	Subtidal		Estuarine waters
		Intertidal	Unconsolidated bed	Intertidal mudflats
			Emergent	Salt marshes
			Forested	Mangrove, tidal forest
	Lacustrine/Palustrine	Permanent/Seasonal		Brackish/saline lagoons
				Coastal fresh lagoons
Inland	Riverine	Perennial		Permanent rivers/streams
			Emergent	Inland deltas
				Intermittent rivers/streams
		Intermittent	Emergent	Floodplain wetlands
	Lacustrine	Permanent		Permanent freshwater ponds
		Seasonal		Seasonal freshwater lakes
		Permanent/seasonal		Permanent/seasonal saline lakes and marshes
	Palustrine	Permanent	Emergent	Permanent freshwater ponds and marshes
				Open peat bogs and fens

				Alpine/tundra wetlands
			Shrub dominated	Shrub-dominated swamps
			Forested	Freshwater swamp forest
				Peat swamp forest
		Seasonal	Emergent	Freshwater springs/oases
				Seasonal freshwater marsh
	Geothermal			Geothermal wetlands
Human-made	Aquaculture			Fish/shrimp ponds
	Agriculture			Farm ponds, small tanks
				Irrigated land, rice fields
				Seasonal-flooded arable land
	Salt exploitation			Salt pans, salines
	Urban and industrial			Reservoirs, barrages
				Gravel pits
				Sewage farms

Table 4 Wetland classification used in the Directory of Important Wetlands in Australia (ANCA 1996)

Marine and coastal wetlands	Inland wetlands	Peatlands
Marine waters	Permanent rivers and streams	Alpine and tundra wetlands
Subtidal aquatic beds	Seasonal and irregular rivers and streams	Freshwater springs, oases and rock pools
Coral reefs	Inland permanent deltas	Geothermal wetlands
Rocky marine shores	Riverine floodplains	Inland subterranean karst wetlands
Sand, shingle or pebble beaches	Permanent freshwater lakes	Human-made wetlands
Estuarine waters	Seasonal/intermittent freshwater lakes	Water storage areas
Intertidal mud, sand or saltflats	Permanent saline/brackish lakes	Farm/stock ponds, and small tanks
Intertidal marshes	Seasonal/intermittent saline lakes	Aquaculture ponds
Intertidal forested wetlands	Permanent freshwater ponds, marshes and swamps on inorganic soils	Salt pans
Brackish-saline lagoons	Seasonal/intermittent freshwater ponds and marshes on inorganic soils	Excavation pits
Freshwater lagoons	Permanent saline/brackish marshes	Wastewater treatment ponds
Non-tidal freshwater forested lagoons	Seasonal saline marshes	Irrigated land and channels
	Shrub swamps	Seasonally flooded arable land
	Freshwater swamp forest	Canals

Table 5 Classification of wetlands using geomorphic and hydroperiod characteristics (Semeniuk and Semeniuk 1997).

	Landform				
Hydroperiod	**Basin**	**Channel**	**Flat**	**Slope**	**Highland**
Permanent Inundation	Lake	River	-	-	-
Seasonal Inundation	Sumpland	Creek	Floodplain	-	-
Intermittent Inundation	Playa	Wadi	Barlkarra	-	-
Seasonal Waterlogging	Dampland	Trough	Palusplain	Paluslope	Palusmont

Table 6 Information categories used in the Directory of Important Wetlands in Australia (ANCA 1996)

Information category	Comments
Name of wetland	Commonly used name of the site
Reference number	Each wetland has been allocated an individual number in alphabetical order and cross referenced to the biogeographical region and the state/territory where it occurs.
Location	Latitude and longitude at the centre of the site.
Area	Hectares
Elevation	Metre above sea level (m asl)
Other wetlands in same aggregation	Listed by reference number
Wetland type	Coded against the classification system
Criteria for inclusion	Coded against the criteria used to justify inclusion as a site of national importance.
Site description	Description of the important characteristics of the site under subheadings – physical, hydrological, and ecological features.
Significance	Significance of the site within the bioregion under the subheadings – notable flora, fauna, and social and cultural values.
Land tenure	Ownership of the site and surrounding land.
Current land use	Human uses of the site and surrounding land.
Disturbances or threats	Current and/or potential direct or indirect human activities at the site or in the catchment that may have a detrimental effect on the ecological character of the wetland.
Conservation measures taken	Details of management plans and conservation listings.
Management authority and jurisdiction	Management agency
Compiler and date	Name of individuals and organisation that supplied the information.

Table 7 Wetlands in the biogeographical regions used by Finlayson et al (1997) as the basis of a review of wetlands of the Wet-Dry tropics. The information is derived from the Directory of Important Wetlands in Australia (ANCA 1996). (NA – no information available)

Biogeographical Region Name	**Code**	**Wetland name**	**Area (ha)**
Burt Plain	BRT	NA	NA
Central Amhem	CA	NA	NA
Central Kimberley	CK	Tunnel Creek	NA
		Windjana Gorge	20
Cape York Peninsula	CYP	Archer Bay Aggregation	29 911
		Archer River Aggregation	149 761
		Bull Lake	26
		Cape Flattery Dune Lakes	44 034
		Cape Grenville Area	7 304
		Cape Melville - Bathurst Bay	5 480
		Harmer River - Shelburne Bay Aggregation	31 751
		Jardine River Wetland Aggregation	81 740
		Lloyd Bay	15 682
		Marina Plains - Lakefield Aggregation	392 333
		Newcastle Bay - Escape River Estuarine Complex	42 307
		Northeast Karumba Plain Aggregation	182 418
		Northern Holroyd Plain Aggregation	1 114 324
		Olive River	17 609
		Orford Bay - Sharp Point Dunefield	17 239
		Port Musgrave Aggregation	52 685
		Princess Charlotte Bay Marine Aggregation	87 835
		Silver Plains - Nesbitt River Aggregation	44 834
		Skardon River - Cotterell River Aggregation	63 194
		Somerset Dunefield Aggregation	8 095
		Temple Bay	4 424
		The Jack Lakes Aggregation	35 054
		Violet Vale	1 896
Daly Basin	DAB	Daly River Middle Reaches	NA
Dampierland	DL	Bunda Bunda Mound spring	22
		Camballin Floodplain (Le Lievre Swamp System)	30 000
		Eighty Mile Beach	40 000
		Geikie Gorge	130
		Roebuck Bay	50 000
		Roebuck Plains System	48 340
		Willie Creek Wetlands	20
Gulf Fall and Upland	GFU	Lawn Hill Gorge	1 133
		Mataranka Thermal Pools	<100

Great Sandy Desert	GSD	Dragon Tree Soak	5
		Lake Dora (Rudall River) System	32 000
		Mandora Salt Marsh	80 000
		Rock Pools of the Breaden Hills	NA
		Karinga Creek Palaeodrainage System	30 000
		Lake Amadeus	103 700
Gulf Coastal	GUC	Borroloola Bluebush Swamps	80
		Limmen Bight (Port Roper) Tidal Wetlands	184 400
		Port McArthur Tidal Wetlands Systems	119 000
Gulf Plains	GUP	Bluebush Swamp	879
		Buffalo Lake Aggregation	1 909
		Dorunda Lakes Area	6 801
		Forsyth Island Wetlands	6 388
		Lignum Swamp	282
		Macaroni Swamp	258
		Marless Lagoon Aggregation	167 009
		Mitchell River Fan Aggregation	714 886
		Musselbrook Creek Aggregation	45 157
		Nicholson Delta Aggregation	63 640
		Smithburne - Gilbert Fan Aggregation	250 320
		Southeast Karumba Plain Aggregation	336 233
		Southern Gulf Aggregation	545 353
		Stranded Fish Lake	67
		Wentworth Aggregation	82 430
MacDonnell Ranges	MAC	NA	NA
Northern Kimberley	NK	Drysdale River	5 100
		Mitchell River System	NA
		Prince Regent River System	NA
Ord-Victoria Plains	OVP	Birrindudu Waterhole and Floodplain	19 000
		Nongra Lake	6 000
Pine Creek Arnhem	PCA	Katherine River Gorge	NA
Sturt Plain	STU	NA	NA
Tanami	TAN	Lake Gregory System	38 700
		Lake Surprise (Yinapaka)	800
Top End Coastal	TEC	Adelaide River Floodplain System	134 800
		Kakadu National Park	234 450
		Arafura Swamp	71 400
		Blyth-Cadell Floodplain and Boucat Bay System	35 500
		Cobourg Peninsula System	84 000
		Daly-Reynolds Floodplain-Estuary System	159 300
		Finniss Floodplain and Fog Bay System	81 300
		Mary Floodplain System	127 600
		Moyle Floodplain and Hyland Bay System	48 100

		Murganella-Cooper Floodplain System	81 500
		Port Darwin	48 800
Victoria Bonaparte	VB	Lake Argyle	74 000
		Lake Kununurra	2 500
		Ord Estuary System	94 700
		Parry Floodplain	9 000
		Legune Wetlands	5 000

The role of GIS and remote sensing technology

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Abstract

The role of this paper is to present a broad overview of the current capabilities of natural resource inventory, spatial analysis and modelling using geographic information systems (GIS) and remote sensing (RS) technologies with particular reference to wetland environments in northern Australia. The underlying theme is that advances in technology continue to facilitate the study of large, relatively unpopulated and inaccessible areas like wetlands and savannas in northern Australia and these provide valuable information for tropical environmental management information and decision support systems.

Keywords: inventory, geographical information system, remote sensing

1 Introduction

Wetlands in northern Australia are extensive, play a major role in the environment, and are in many cases relatively unspoilt by human impact. Their importance as a natural resource is highlighted in the papers that accompany this one. In order to maintain and enhance wetlands as a natural resource, environmental managers need information on which to base their decisions. Some of this information is political, legal, and socio-economic but in many respects the most significant component is environmental. Managers need to know the current status of natural resources, to monitor changes in these resources over time, and to predict and evaluate the impact of proposed courses of action.

1.1 GIS provides a framework

Geographic information systems provide the necessary framework to input, manipulate, analyse, and retrieve spatial data and related attributes of spatial features. They can store data collected from a variety of sources and bring it together in a way that enhances the information that can be gleaned from it. The enhancement may simply take the form of a map of a particular area with specified information included in it, or may involve spatial analysis and modelling. Data stored may be relatively static, such as soils maps, or dynamic, such as fire scars. An important source of dynamic data is remotely sensed data from spaceborne or airborne platforms as it can provide a synoptic view of large areas.

1.2 Wetland inventory, monitoring and modelling

Effective management of wetlands in northern Australia therefore requires information from a GIS which in turn provides a framework for data from many sources including remotely sensed data. In the first instance, the application of these technologies is required to provide baseline information for wetland inventory. When this baseline information has been collated it is possible to begin monitoring change and model alternative management scenarios. This paper provides an introduction to GIS and remote sensing technology and their integration for wetland.

2 Geographic Information Systems

There are as many definitions of geographic information systems as there are authors and an exhaustive definition will not be attempted here. The important characteristics of a GIS in the context of wetland inventory are that it provides a framework for the collation and analysis of spatial data from disparate sources as well as information for input to management decision support systems. The requirements for a GIS with a particular emphasis on data are briefly discussed hereafter as well as the outcomes necessary for a successful GIS implementation.

2.1 GIS components

The essential components of a GIS are easily identified – hardware, software, data and people. Hardware includes computing power, data storage and backup facilities, and output in the form of monitors or hard copy plots or reports. Software provides a means for the user to easily use the hardware to manipulate, analyse and visualise the underlying data. Data, not to be confused with information, an obvious prerequisite to any wetland GIS application, is discussed further below. People, perhaps the most important component, need knowledge, understanding and skill in both wetland environmental management and GIS to enable useful outcomes from the system. It is the responsibility of the manager to assemble these components in a way that produces useful information for decision making.

In general, the cost, availability, and complexity or depth of knowledge of each of these components is inter-related and dependent on the scope and complexity of the task at hand. This relationship can be visualised using a graph with four axes, each representing a component (figure 1). An arrow on each axis indicates increasing cost and complexity. For example, low-end hardware and software might be a PC with Windows 95 and desktop mapping software, whereas a high-end system might be a Unix workstation or supercomputer with specialised GIS software. Low-end data requirements might be readily available vector or raster data whereas high-end requirements could be a comprehensive digital elevation model for an area. People skills can range from a PC end user with limited or no training in GIS/RS to experienced and highly qualified professionals.

The bottom line of this section is to emphasise that to achieve a successful GIS implementation where cost and benefits are balanced, management generally need to keep operational activities at the low end of these scales. High-end activities should be entered into sparingly, perhaps through out-sourcing or consultancies, to achieve specific one-off tasks or develop protocols for operational activities that once determined can be migrated to a less complex and more cost-effective environment.

2.2 GIS data

GIS data can come in digital or analogue forms. Analogue data can be an important source of information since most information collected in the past was recorded and mapped using analogue techniques. Currently, with the notable exception of aerial photography, most information is recorded in a digital format. Historical information is important when attempting to establish baseline data or determine whether change has taken place and it should not therefore be overlooked. It does need to be converted to a digital form before it can be integrated into a GIS and this can be an expensive exercise.

Geographic information has location, time and attributes. Location is generally expressed in a coordinate system often 2-dimensional but sometimes 3-dimensional (for example, digital elevation data). Time is not a dimension that is well handled at present by conventional GIS and is usually the date of data collection. Attributes include any information relating to the spatial features in the GIS (including dimension, images, text, video, sound etc). It is important to bear in mind that data is only a representative sample of the real world that is being modelled in the GIS.

Data is generally recorded and stored in one of three formats:

- Vector data are represented by coordinate pairs that on their own are point features (for example, bores or sample sites). A series of coordinate pairs is a line feature (for example a road or river), and a series of coordinate pairs that start and finish at the same point is a polygon or area feature (for example, vegetation types or land use). This method of recording and manipulating spatial information works well for some data and is efficient in terms of storage space.
- Raster data are stored in a grid cell or pixel format the size of which can vary. This variation in cell size is called the spatial resolution and may be dictated by the resolution of the data available or the task for which the data is required. Digital remotely sensed data is stored in this manner (discussed separately below) and it is often used where continuous surfaces are of interest (eg digital elevation models).
- Attribute data are conventionally stored in a relational database management system (RDBMS). Each spatial object in the raster or vector spatial database has a unique identifier that is used to provide a key to the related aspatial or attribute data associated with those features. The key can be used either way – spatial features can be selected by attribute selection in the RDBMS or attributes can be listed for spatial features identified through a spatial selection.

An important aspect of all spatial data is that they must be registered to a common coordinate system if it is to be useful. Commonly, a map projection such as AMG (Australian Map Grid) or geographic latitude and longitude is used to register all data. This is a necessary prerequisite to any comparison or overlay analysis. Although space precludes their discussion it should be noted that spatial resolution and scale are important issues to consider when collating and analysing data in a GIS.

2.3 GIS outcomes

It is particularly important from a management perspective to have a clear picture of what might be expected to come out of a GIS implementation. In the first instance, a GIS can provide the efficient storage and retrieval of data with spatial characteristics that might otherwise be difficult to manipulate. The retrieval can take the form of maps and reports that contain selected themes for areas of interest and characteristics of the spatial features can be found. These may be spatial characteristics (area, length, perimeter etc) or aspatial attributes (description, address, owner etc). There are many advantages over traditionally prepared maps including the ability to quickly and easily generate updated maps when new information comes to hand.

These factors alone are enough for many people and organisations to implement GIS but once the system is in place and baseline data has been collated users begin to look for answers to more complex questions which require some analysis of the data. Typically these will include questions relating to suitability of specific areas for a defined use, risk analysis, and the monitoring of change over time. As the database matures in terms of quantity and quality of data it becomes possible to use the GIS to assist in simulations, and the evaluation of alternative courses of action. Modelling may be done within the GIS or involve the integration of external models (for example, hydrological models).

A GIS is a tool for the use of management and the outcomes need to be integrated with other sources of information. GIS can provide useful ways for managers to visualise impacts of various courses of action and demonstrate these to others (perhaps their managers or funding bodies). A map can be worth a thousand words!

3 Remote sensing technology

The extent and remoteness of many of the wetlands in northern Australia combined with their inherent inaccessibility make remotely sensed imagery the only viable option for collecting synoptic data on a regular basis. After processing, this data then becomes input to the GIS and contributes to the flow of information available to environmental managers.

Remotely sensed data is a surrogate for the actual features of interest on the ground and is collected in a manner that suits integration in GIS. Satellite data contain attribute information (a spectral response) about a particular location on the ground at a particular time.

Remotely sensed data offers significant advantages in that it presents a synoptic view of the earth at periodic intervals, is (with some limitations outlined below) readily available and accessible, and it provides a relatively economical means to build a spatial database. It also offers the possibility of visiting and revisiting the past through the use of archived data. Aerial photographs provide the longest lived historical record of most areas but even satellite imagery can be obtained for the last twenty years.

Like most new technologies, remote sensing brings challenges as well as advantages. The large number of variables that play a role in the data collection can make it hard to interpret and use in a consistent manner. For example, features of interest such as vegetation will appear markedly different between seasons. These changes (for example, greening and browning) can come about over very short time periods. They can also consume large amounts of storage space and processing capacity.

3.1 Remotely sensed data

Remotely sensed imagery is generally collected through measurement of the electromagnetic spectrum. The signals may be passively generated through the reflection of light energy from objects on the surface of the earth such as aerial photographs or optical satellite imagery. Alternatively, signals may be actively generated from airborne or spaceborne platforms using radar or laser technology. The data collected is stored in raster format as an image made up of one or more bands (the wavelengths measured) each of which has pixels (grid cells) with a measured value (usually between 0–255) which is the attribute of the pixel. This information is then processed and interpreted to identify objects and/or areas of interest using digital image processing techniques.

3.2 Digital image processing

Digital satellite imagery contains huge amounts of data that generally needs to be reduced in order to be useful as input to a GIS and consequently provide information for environmental managers. For example, a Landsat Thematic Mapper (TM) image has 7 bands of information at a spatial resolution of 30 metres (for 6 bands and 120 metres for the seventh). Techniques for data reduction are well established and a number of computer software applications are available to assist in this process. A brief description of the standard method follows.

Each pixel represents a location on the ground at a particular time and an attribute that is a measurement of the average reflectance of the spatial objects on the ground in that cell. Since the energy reflected, absorbed and transmitted by different objects varies it is possible to differentiate between objects and identify those of interest. After pre-processing (eg eliminating atmospheric effects), enhancement techniques can be used to highlight areas or features of interest. Once identified, the spectral characteristics can be described as a spectral signature. This signature can then be used to identify other similar features in the image using classification functions available in image processing software.

Following classification, post-processing techniques are required to make the data suitable for integrating into a GIS. The most important of these are smoothing the classified image to create a thematic map and registering the image to known coordinates on the ground. Ground truthing of the results of this data reduction process is absolutely essential. This involves going out into the field to sites identified on the image (usually located using a GPS receiver) and ensuring that the classification is accurate. Without an evaluation of this nature the quality of the data cannot be relied upon by managers. There are other techniques for verification of results within a GIS which can augment or reduce the need for field work which may be particularly difficult and/or expensive in wetlands during the Wet season.

4 Integration of GIS/RS/MIS

Management requires information to make decisions. This information is normally the synthesis of information integrated into a management information system from a number of sources, a significant one of which is the GIS. The GIS, in turn, also integrates data from a number of disparate sources including remotely sensed data. The GIS also provides information to aid the data reduction process for remotely sensed data. For example, a digital elevation model may be used to reduce the area to be classified for mangrove vegetation by masking out areas above a certain elevation in the image. This reduces the chance of an overlap in spectral signatures of different vegetation types.

The integration path for the application of these techniques to wetland environmental management should now be clear. Remote sensing data provides synoptic and dynamic data at varying spatial and temporal resolutions which after digital image processing is used as input to a GIS where analysis and modelling can be performed. The output of the GIS is then fed up the line directly to management or into a management information or decision support system.

5 Conclusion

A summary of how these technologies have been, and can be, used in wetland management follows.

Wetland information that may be derived from remotely sensed imagery includes:

- extent of wetlands
- type of wetland
- characterise wetland land cover type

- identify submergent/emergent wetlands
- provide information about quality

When this information is added to a GIS and integrated with data from other sources the following applications are possible:

- inventory (eg what is the extent of wetlands in northern Australia?)
- analysis (eg what changes have occurred in that extent over the past X years?)
- modelling (eg predicting flood levels given certain parameters)

The authors have prepared a comprehensive bibliography of GIS, remote sensing and wetlands which is published as a companion to this paper. The reader is urged to turn to this for detailed discussion and examples of wetland applications. There is also a wealth of material on the Internet, particularly relating to the North American continent, much of which is germane to the application of these technologies in northern Australia.

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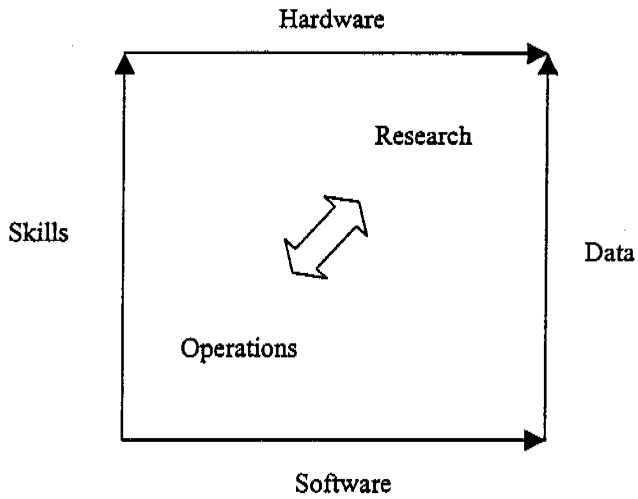
The relationship between the components of a GIS and operational/research activities.



Ecological design and survey

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Abstract

The collection of information for use in wetland management needs to be preceded by a series of steps to ensure that time and resources are well spent. This planning phase should include clear identification of the issue(s) to be addressed and what stakeholders perceive to be the values of the wetland. From this base, objectives can be formulated and the appropriate variables for study selected. In wetland studies, variables will generally include those that are intrinsic to management issues (eg pest species or species of economic importance) or some type of ecological indicator. Design of sampling programs will be based on the objectives but may be constrained by logistical factors (suitable control sites, access, human resources and funding). A BACIP monitoring design is described as an example of a statistically rigorous approach that has been used successfully in the Wet-Dry tropics.

Keywords: objectives, biological indicators, statistical inference, study design

1 Introduction

Careful planning and design of wetland sampling programs should allow for the generation of information of direct relevance to managers and stakeholders. To emphasise the importance of the planning and design phase, it has been suggested that the design stage of a long-term monitoring program should account for some 10% of the projected 20-year operating costs, although this would be proportionately less for shorter term programs (Ward et al 1990). The current paper provides a provisional framework for how to approach the planning of ecological surveys, and concentrates on aspects of design as they relate to sampling in tropical wetlands. Statistical considerations are also discussed in relation to sampling designs for wetlands but detailed explanation of methodology is not attempted.

2 A framework for approaching wetland management issues

Effective wetland management and protection requires a range of types of information and knowledge about the constituents and processes that define wetlands. Scientists may be approached to provide this type of information to managers or other stakeholders. Some of the types of information necessary for the ecological characterisation of wetlands have been discussed previously (Finlayson 1996 a,b) but before such information is actually gathered we need a framework to ensure the data gathering process is effective (Bunn et al (?) Finlayson & Mitchell 1998). Such a framework has been adapted from the current revision of the ANZECC (ANZECC in prep) water quality guideline's section for biological assessment of water quality (fig 1). Whilst not attempting to be prescriptive, the framework provides a sequence of key steps to be considered in the planning phase of wetland studies.

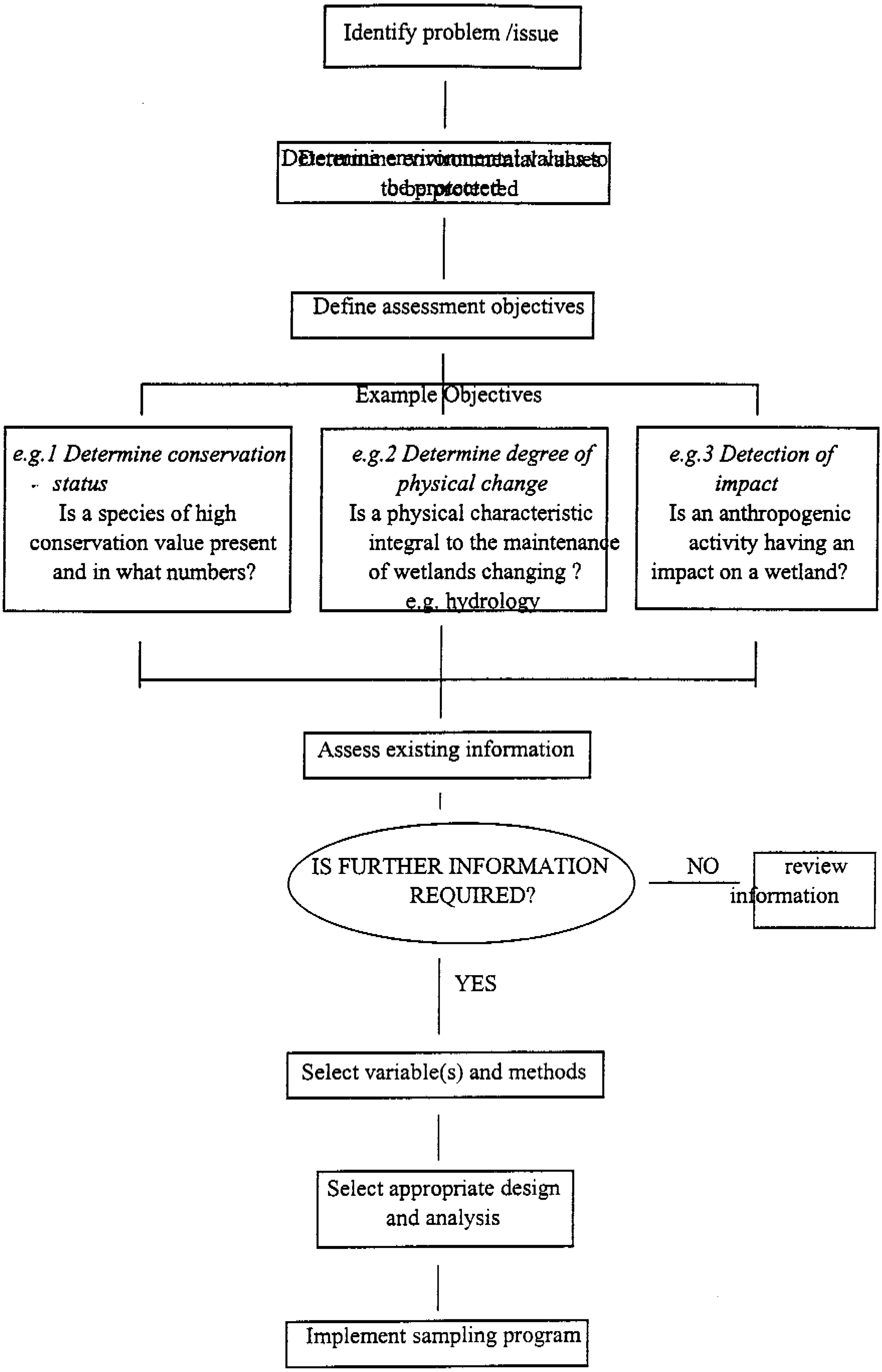

Figure 1 A framework for determining information needs to address wetland management issues

A review and sound knowledge of existing information is a key element in developing data-gathering programs. Information may be found in published research, management, monitoring and policy documents and from local knowledge (Finlayson 1996 a,b). Existing information can be used to help formulate objectives and decide on whether a sampling program is necessary or if review and synthesis of current information will suffice. At a basic level researchers need to determine, for the wetland of concern, what government policies pertain to the protection and management and whether guidelines and/or compliance standards are in place for the collection and analysis of variables of interest (eg ANZECC in prep for studies based on water quality).

Linking the scientific aims of any information-gathering exercise (whether it be data collection or review) to the needs of managers and stakeholders of freshwater resources has become an increasingly necessary action (Finlayson 1996 a,b); this is well exemplified in the current review of Australia's national water quality guidelines (ANZECC in prep). The current water quality guidelines recognise six environmental values ranging from ecosystem protection to maintenance of water quality for various uses such as human consumption and agriculture. Some of the benefits and values of wetlands that may need to be protected have been classified as functions, products and attributes (Finlayson 1996 a,b). Valued functions of wetlands include flood mitigation and retention of nutrients, valued products include wildlife resources, forage resources and water supply, while valued attributes of wetlands include biological diversity and cultural features. The design of sampling programs for wetlands needs to ensure that the resulting information can be used to address whether or not particular values are being protected (fig 1).

Setting of objectives provides the justification for data collection and should also allow the effectiveness of programs to be evaluated (Maher & Norris 1990). Basing sampling programs solely on logistical considerations (ease of access and choice of variables that are easy to measure) rather than to provide information for a defined objective, has resulted in considerable data being collected without a means of converting them into information and contributing to management decisions (Ward et al 1990; Finlayson & Mitchell 1998). Ideal objectives have the following features (from Maher & Norris 1990):

1. They are clearly and concisely defined
2. Specify what is to be achieved
3. Deal only with attainable results and do not express idealistic aspirations
4. Indicate when each stage will be completed

3 Selection of variables

The types of variables used in the study of aquatic ecosystems have traditionally been split into two broad categories: 1) physical and chemical variables such as flow, depth, and chemical constituents of water, sediments etc; and 2) biological variables selected from the range of resident flora and fauna. While this paper will focus on the use of these types of variables in wetland sampling programs, it is worth noting that the success of wetland management strategies may also be assessed by socioeconomic indicators where socioeconomic health is linked to ecosystem health. Examples of socioeconomic indicators include: 1) human health; 2) sustainable human use of resources; and 3) favourable public perception of the quality of life and the environment (Cairns et al 1993).

Biological variables are generally used when organisms within wetlands are the primary source of interest or they provide information that physical and chemical variables cannot (table 1). Conversely, physical and chemical variables are most often used in relation to compliance criteria and to explain biological processes (table 1). Assessment of water quality has traditionally used physical and chemical variables (Norris & Georges 1986) although the importance of biological variables in the assessment of ecosystems has been emphasised more recently (eg Metcalfe-Smith 1994, ANZECC in prep). Biological, physical and chemical methods are all relevant for assessing ecosystem health and the problem must dictate the methods to be employed for this assessment, not the reverse.

Table 1 A comparison of objectives for sampling programs using physical and chemical versus biological variables.

Objectives of studies using physical and chemical variables	Objectives of studies using biological variables
1. Compliance monitoring eg discharge regulations for industry, human health concerns.	1. To directly determine the effects of contaminants on living organisms.
2. To explain and predict biological processes eg sampling nutrient levels in water to predict algal blooms.	2. To provide an integrated assessment of environmental conditions over time including multiple stresses and cumulative impact.
3. Early warning of impact (where levels known to effect biota can be detected).	3. Early warning of impact (where levels of physical and chemical variables known to effect biota cannot be detected).
	4. To assess the effect of activities that do not result in physical and chemical alterations eg flow alteration, habitat destruction and overharvesting.
	5. To assess conservation status of species.

Assuming biological variables are accepted for use in a sampling program, the next issue is to select the appropriate ones (fig 1). The choice of variables can proceed hierarchically in the manner of the proposed framework (fig 1). Firstly the variable must be intimately related to management goals. Secondly measures of the variable must lie within the appropriate temporal and spatial scales relative to the management goals (ie be able to address the objectives) and thirdly methodologies for their use must have been developed (Cairns et al 1993).

Biological variables intrinsically tied to wetland management goals will include species of economic or conservation significance (eg barramundi or magpie geese). Likewise, studies of pest species such as feral pigs and *Mimosa* will require information on these taxa (and probably variables related to their potential impact). Alternately, selection of *indicators* of ecological health may be appropriate.

Indicators can be defined in a very broad sense as 'measurable variables for characteristics of an ecosystem' (Grillas 1996). Unlike the biological variables mentioned above, indicators may not be of interest in themselves (eg macroinvertebrates, algae) but they are able to reflect something about the broader ecosystem. Biological indicators have been defined as 'a species (or species assemblage) that has particular requirements with regard to a known set of physical or chemical variables such that changes in presence/absence, numbers, morphology, physiology, or behaviour of that species indicate that the given physical or chemical variables are outside its preferred limits' (Johnson et al 1993). A number of attributes of good biological indicators have been recognised (Johnson et al 1993):

1. Taxonomic soundness (ie species have been confidently separated) and easy recognition by the non-specialist. This ensures consistent identification by a broad range of people, eg fish.
2. Cosmopolitan distribution. This means that comparison between all sampling sites is possible because the indicator occurs in them all. It also means the organism can be affected by a range of environmental perturbations in many different types of aquatic systems and habitats, eg algae and macroinvertebrates.
3. Numerical abundance. Reduces sampling effort and is necessary for statistical purposes, eg macroinvertebrates.
4. Low genetic and ecological variability. Particularly important for impact assessment to ensure differences are due to the impact and not natural variability in the indicator measured.
5. Large size. Easier to sample/observe, eg birds, macrophytes.
6. Limited mobility and relatively long life history. Limited mobility will facilitate collection and reduce avoidance of impacts while the life history needs to be long enough for the organism to be collected/observed with ease and be exposed to potential impacts, eg macrophytes, macroinvertebrates.
7. Ecological characteristics are well known. This allows accurate interpretation of patterns and changes in distribution and abundance of the indicator. Not many indicator groups satisfy this criterion.
8. Suitable for use in laboratory studies. Testing of cause and effect can only theoretically take place in the controlled environment of the laboratory, eg microinvertebrates.

The relative importance of the above attributes in determining indicator selection will vary according to the objectives as described in the following section. The most common aquatic indicators used in impact assessment of freshwater systems are macroinvertebrates, fish, algae and macrophytes. Non-aquatic indicators of interest in tropical wetlands include birds, mammals, amphibia and reptiles.

3.1 Indicator organisms, populations and communities

Biological indicators can be studied at a number of levels to tell us something about the health of wetlands. At an organism level, a variety of measures from biochemical to life-history changes and bioaccumulation may be measured in individuals. For example, in the Alligator Rivers Region (ARR) freshwater mussels (*Velesunio angasi*) have been used as indicators through bioaccumulation and growth and mortality studies (Humphrey et al 1990). Bioaccumulative indicators are a 'special kind of indicator organism that accumulate pollutants from their surroundings and/or food so that an analysis of their tissues provides an estimate of environmental concentrations of pollutants' (Johnson et al 1993). In the ARR, mussels have been analysed for their accumulation of stable and radioactive metals that may be waste products from mining (Humphrey et al 1990).

The use of biological indicators at the population (one species) or community (more than one species) level is concerned less with directly measuring the physiological responses of individuals than it is with the ultimate, integrated expression of a response to the environment, ie the presence, absence and abundance of species. Population studies are often concerned with variables such as density, age structure and sex ratio, while community studies often deal with changes in community structure. Changes in community structure can be in the form of simple changes in biomass, changes in the relative abundance of species, disappearance of species and combinations of these (Hellawell 1986). Structural changes often reflect changes in how the community is functioning. For example, discharge of domestic sewage to streams can cause dramatic changes in macroinvertebrate fauna – some taxa sensitive to chemical changes will disappear and some that can feed on the organic material will dramatically increase in numbers (Campbell 1978).

Deciding upon indicator populations versus communities should not be viewed as competing tasks, but rather as complementary tasks with each addressing different objectives. Indicator species appear to be most effective at: 1) directly measuring progress towards the restoration and maintenance of populations that possess commercial and/or social value, and 2) tracking progress towards remediation of specific forms of environmental impact by identifying species known to be especially sensitive to individual stressors. In contrast, a community level approach to wetland monitoring provides a more robust assessment of ecosystem health in a region as it is impacted by the cumulative effects of many stressors ranging from persistent contaminants to the introduction of exotic species (Cairns et al 1993). Use of communities also has inherent statistical advantages (Humphrey et al 1995).

4 Study design

The three main study types undertaken to address wetland management issues ie survey, surveillance and monitoring, are detailed in Finlayson 1996a. Design will be different for each of the study types reflecting differences in their scope and objectives. System understanding programs (survey and surveillance) will have broad objectives while monitoring will have narrowly defined or limited objectives (Maher & Norris 1990). An implicit feature of different study types and objectives is their differing requirements for statistical inference. In statistical terms, a study design will have inferential power if a change can be linked to an identified source of impact. This often relates to separating natural variability in the biological indicator from variability caused by the impact, eg being able to separate changes in a wetland plant community caused by the removal of buffalo from seasonal or interannual changes in plant communities. Another aspect of statistical inference relates to the ability to state the magnitude and ecological significance of the change, eg a change has been detected but changes of such magnitude and for this duration are not uncommon in such ecosystems (Humphrey et al 1995). Therefore, in the spectrum of study types, surveys would be expected to have little or no need for statistical inference while at the other extreme, monitoring programs would have a strong need for statistical inference.

4.1 Where to sample

Study design in the statistical sense involves decisions on the spatial distribution of sampling stations and decisions on the frequency of sampling at those stations. In deciding where to take samples (selection of sampling sites), the objectives as well as ecological, statistical and logistical factors need to be considered. The objectives of a study will generally dictate the broad or macro level of site selection such as different classes of wetland or types of river. For example, in the ARR you may distinguish between different billabong types such as backflow billabongs at creek junctions versus floodplain billabongs. Ecological factors influence site selection at the micro level and define the exact places to be sampled, eg where in the backflow billabong will the samples be taken – in open water, at the edge, at a particular depth? Consideration of site selection at the micro level is determined by the need to obtain a 'representative' sample within the macro location (Ward et al 1990).

One of the most important statistical aspects of site selection is the provision of control sites. Controls provide a benchmark against which changes in the indicator in the impacted areas can be judged, and are thus a necessary component of studies where statistical inference of ecological change is required. Such controls need to be biophysically similar to the site(s) or area(s) subject to the putative impact and also need to be free of other highly localised disturbances unrelated to the putative impact (ANZECC in prep). The nature of tropical wetlands is such that finding control sites can be problematic, eg wetlands can form contiguous systems or large interconnected complexes (Storrs & Finlayson 1997) which can make finding control sites that are independent of the impacted sites difficult. This illustrates another statistical consideration of site selection, namely independence with respect to the indicator being used.

Many statistical methods also require samples to be taken at random. In simple random sampling, every sampling unit in the population (of your indicator organisms) has an equal chance of selection. In practice, many studies in tropical wetlands are designed to sample different micro locations or strata (as described previously). Random selection of sites within these strata then constitutes stratified random sampling. From a statistical viewpoint these 'strata' should be more homogeneous than the whole system and should be well defined areas of known size (Elliott 1977). For example, in sampling macroinvertebrates, zones of flowing waters in the ARR have been split into different substrate types (cobble, sand and vegetated) which are quite distinct and support different communities.

Logistical considerations such as access, funds and human resources may influence the location of study sites and how many sites are used within the constraints of the previous factors. A major logistical constraint in the location of sampling sites in tropical wetlands is access. If access is required during the Wet season, roads may be cut off by floodwaters or impassable if unsealed. Sites may need to be located where there is easy access by boat in the Wet or near helicopter landing areas. The number of sample sites to be employed is usually a function of the budget available for sampling, the size of the system and the variability of the target indicators (a consideration in the statistical power of the design – described in section 5).

4.2 How many samples to take

In the study design phase, the number of samples to be taken on a given occasion and how many sampling occasions there should be must be considered. There are two reasons for replication in a study: 1) to estimate the value of a given measure, such as mean density of individuals, with a desired degree of precision and risk of error (common in surveys and population studies at single sites); and 2) for statistical inference about differences, as mentioned previously (Resh & McElravy 1993). Environmental variability is a fundamental problem facing those concerned with assessing changes in space and time. Conclusions that a given environmental measure actually differs at particular sites or times can only be made when observed differences in means between sites/times are greater than would be expected based on observed variation within sites or times (Norris & Georges 1986).

There are a number of mathematical procedures for estimating the number of replicates required for a study (Elliott 1977). The actual number will depend on: 1) the size of the mean; 2) the degree of aggregation; and 3) the degree of precision and statistical power required, ie using a small-sized quadrat is useful in increasing sample replicates but not if mean values are low and zero counts of abundance become common. The greater degree of aggregation the more sample replicates required (if mean density is constant). The higher the degree of precision required, the more sample replicates required (Resh & McElravy 1993). Generally a compromise needs to be made between statistical accuracy and the labour required to collect and process samples.

4.3 When to sample

As with other aspects of sampling design, the timing of sampling will be intricately linked to the study objectives (fig 1). A particular event of importance may be targeted and this will dictate sample timing. For example, fish migration studies in the ARR occur at the end of the Wet season as fish move from spawning grounds on the floodplain to permanent waters in the upper reaches of streams (Humphrey et al 1990). Time of day may also be important for surveying some animals eg fish.

In a broader context, timing of sampling in tropical wetlands is often related to the strong and predictable seasonal variation in water regime and species' response to this. Seasonal variation in distribution, abundance or behaviour of the selected indicator may all influence the timing of sampling. For example, sampling of macroinvertebrate communities in streams and billabongs in the ARR for monitoring purposes occurs at the end of the Wet season when abundance and diversity are at a peak (eg Outridge 1988). Conversely, mapping of vegetation in billabongs may occur during the Wet season when aquatic plants flower and reach their peak biomass (Finlayson et al 1989, Finlayson et al 1994).

Statistical considerations in the timing of sampling relate to studies that seek to identify changes in some particular variable over time. The most rigorous of sampling designs will have samples taken before and after a change or impact (ANZECC in prep). In many cases, however, pre-impact data may not be available such as for uncontrolled or unforseen impacts. In some instances historical information collected for other purposes may serve as a suitable reference for other issues (again emphasising the importance of a thorough knowledge of existing data). For example, plant surveys conducted in the ARR to determine potential effects of mining may be useful for assessing the effect of the introduction of weeds such as *Salvinia* which is present now but was not present at the time of the original survey. Another alternative for dealing with a lack of pre-impact data is comparison of sites currently impacted with a range of biophysically similar control or reference sites (ANZECC in prep).

5 The BACIP study designs as an example of statistically rigorous design

BACIP is an acronym for Before, After, Control, Impact, Paired differences, which summarises the design structure. A BACIP design involves sampling closely matched, but independent, areas simultaneously at several times before the impact occurs, and for several times after the impact in both impact and control areas. Each time period is summarised not by the individual observations at the control and disturbed sites, but rather by some measure of the difference between the two sites at that time. In a BACIP design employing a number of control locations, if the size of these difference values changes after the impact, the putative impact is inferred to have been responsible for that change. The design assumes that the difference value in the indicator between control and impact areas would have remained the same if the impact had not occurred (Faith et al 1995). For example, BACIP designs have been tested on data from the South Alligator River catchment and have shown a high sensitivity in detecting impacts from a disused mine on the macroinvertebrate community structure of the adjacent creek (Faith et al 1995).

Statistically rigorous designs such as BACIP are appropriate in highly valued environments, such as the Alligator Rivers Region, where even small impacts are of interest to the stakeholders (as is the case with uranium mining). In cases such as these, monitoring study designs are required that allow application of statistical tests with high power. Statistical power refers to the level of confidence that a Type II error has not occurred. Type II errors occur when it is concluded that means are from the same sample population when they are not, eg it is concluded that macroinvertebrate communities were not affected by mine waste water releases when they were. Type I errors, on the other hand, are when it is concluded means are from different sample populations when they are not, eg it is concluded that macroinvertebrate communities were affected by the release of mine waste waters when they were not. Study designs with high statistical power, therefore, are able to guarantee that an impact no greater than a prescribed amount has gone undetected.

The appropriate indicators for BACIP designs are those that are proven to be tightly linked to the potential impact and unlikely to be affected by extraneous natural factors. Pilot studies would generally be required to determine these factors prior to the commencement of the monitoring program itself. It is worth noting, however, that one needs to be cautious about over-reliance on statistical procedures – sound design also requires an understanding of underlying biological processes and careful planning (Humphrey et al 1995).

6 Conclusion

Successful and effective ecological data-gathering requires a planning phase that includes determination of the issues, values of the ecosystem to stakeholders and clear formulation of objectives. Decisions regarding what variables to study and how they should be described or quantified will primarily be a function of these objectives and their inherent statistical requirements, within the limitations of logistical considerations. Tropical wetlands provide a number of unique challenges for ecological study which need to be recognised in the planning and design stage of information gathering.

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Survey techniques for invertebrates

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Abstract

Benthic macroinvertebrates are a popular biological indicator group for assessing the health of aquatic ecosystems. Use of macroinvertebrates requires decisions regarding both sampling and processing strategies for which quantitative, semi-quantitative or qualitative approaches can be employed. Selection of the appropriate techniques is dictated by the objectives of the study, the nature of the habitat to be sampled and available resources for processing. Qualitative rapid assessment techniques have become popular recently because of the large effort often required to process quantitative samples.

Keywords: benthic macroinvertebrate, rapid assessment technique, sampling, sample processing

1 Introduction

The validity of any ecological investigation depends crucially upon the sampling technique and strategy adopted at the outset. Inadequate sampling effort cannot be compensated for by sophisticated analytical techniques. Invertebrates, unlike some other indicators such as fish and vegetation, can only be identified and quantified via collection; visual surveys are not possible. The use of invertebrates in a study also requires consideration of how to process or 'sort' samples given that many sampling techniques result in a mixture of sediment, detritus and animals (Hellawell 1986, Abel 1989, Rosenberg & Resh 1993).

Benthic macroinvertebrates are the most commonly sampled of the invertebrates and refer to those organisms that inhabit the bottom substrates (sediments, debris, logs, macrophytes, filamentous algae, etc) of freshwater habitats for at least part of their life cycle. *Macro*invertebrates are those retained by mesh sizes ≥ 200–500 µm (Rosenberg & Resh 1993). Several reviews have found that macroinvertebrates are the most commonly used group for assessing water quality (Rosenberg & Resh 1993). They have also been used in a wide range of biological sampling programs and for a variety of reasons including: monitoring changes in genetic composition, bioaccumulation of toxicants, toxicological testing in the laboratory and field, and measurement of changes in population numbers, community composition, or ecosystem functioning.

Benthic macroinvertebrates have many of the characteristics for good biological indicators and this explains to a large extent their popularity in water quality studies. As a group they have a large number of species which offer a spectrum of responses to environmental disturbance and can be sampled using simple inexpensive equipment. Their relatively long life cycles and relative immobility mean that benthic macroinvertebrates act as continuous monitors of the water they inhabit, enabling long-term analysis of both regular and intermittent discharges, variable concentrations of pollutants, single or multiple pollutants and even synergistic or antagonistic effects (Rosenberg & Resh 1993).

2 Qualitative versus quantitative sampling

Quantitative sampling allows the absolute abundance of organisms within a designated area to be estimated while qualitative sampling aims to recover a representative range of organisms present in the community. Semi-quantitative sampling is halfway between the two as it provides an indication of the relative abundance of the components of the community but does not enable one to relate them in absolute terms to a defined area or volume of the habitat (Hellawell 1986).

Quantitative sampling is often useful in monitoring studies rather than surveys and surveillance (Abel 1989). This is partly because the data is potentially suitable for analysis by almost any method (within other design constraints). Changes in the abundance of species can also be determined by quantitative sampling eg knowing that the abundance of a species has halved or doubled over time, or that the ratio of abundance of two species has altered, may be of interest in a monitoring program. Problems with attempting quantitative sampling is that estimation of absolute population density is extremely difficult. The pattern of distribution of benthic invertebrates seems to be such that very large numbers of samples are required for reliable estimates of population density. Even to estimate population densities to within ± 20% or 40% of their true values may require several hundred samples (Abel 1989). Another problem is that most commonly-used samplers only sample the top few centimetres of substratum, which can lead to serious errors where significant proportions of animals live deeper within the substratum.

An example of the use of quantitative sampling by ***eriss*** has been in long term monitoring of macroinvertebrate communities of the South Alligator River. Sampling of this river was initiated when mining at nearby Coronation Hill was proposed. Data that was comparable over time, able to detect changes in abundance and could be analysed to give a high degree of statistical inference was required, so a Surber sampler (quantitative technique) was used (Dostine et al 1992).

Qualitative and semi-quantitative sampling techniques are generally most useful in survey and surveillance types of study. The advantages of qualitative sampling techniques are that: 1) they generally do not require elaborate apparatus; 2) they usually catch a high proportion of the total species present at each station; and 3) they often provide fairly comparable figures, especially when the habitat and collector are the same for all samples. Disadvantages are: 1) they cannot be used in deep water; and 2) the samples do not provide estimates of numbers per unit area (Elliott 1977).

An example of qualitative sampling done by ***eriss*** is billabong surveillance carried out over the last two years. In this instance the spatial and temporal range of species present in billabongs was of interest rather than making statistical inference regarding differences in community structure. For this study a dip net (qualitative technique) was used.

3 Description of sampling techniques

3.1 Qualitative techniques

Hand nets (or dip nets) are one of the most versatile implements for qualitative sampling. Essentially a mesh bag attached to a rectangular or triangular metal frame is fitted to a handle or pole. In running water it is held vertically upon the stream bed and an area of the substratum immediately upstream of the net mouth is disturbed by hand or foot. In vegetated areas with no flow the net is swept through the vegetation and may also be used to disturb the underlying substratum. Although the method is qualitative in that the area (and depth) disturbed are not fixed, some operators attempt to minimise this source of variability by sampling for a definite period or by sampling for a fixed distance (Hellawell 1986).

Drift sampling is a passive technique for collecting macroinvertebrates that move into the water column actively or passively and then drift in the current – a mechanism for dispersal and avoidance of disturbance. Drifting animals are sampled by attaching a net to the substrate and leaving it to collect animals. This technique is only appropriate for use in flowing waters and is employed in studies of species that are more easily located in the drift, or more commonly, for looking at sources of colonisation and environmental change. Increased turbidity, for example may trigger drift (Hellawell 1986).

3.2 Quantitative sampling

Surber samplers combine a rectangular quadrat to delineate the area of bed to be sampled and a net into which the disturbed benthic invertebrates are swept by the current. Because Surber samplers rely on flow to wash the disturbed invertebrates into the receiving net they are generally only used in flowing water habitats. As the area of bed to be sampled is fixed, these samplers are quantitative, although the depth to which the operator disturbs the substrate may vary. This means that even these methods may not provide absolute measures of population densities (Hellawell 1986).

Grab samplers are designed to remove a portion of substrate and animals by a biting action. Originally designed for marine work they are used in freshwater situations where there is deep water and fine substratum. A number of different designs of grab samplers exist but they are generally inefficient with particle sizes exceeding 16 mm and where animals are buried more than 3 cm below the surface (Abel 1989). This is because coarse material can get lodged in the mouth of the sampler preventing its closure and thus resulting in loss of sample material.

Air lift or suction samplers use compressed air to scour substrate and raise water, lighter substrate material and fauna as the air ascends within a delivery pipe. The material is then discharged into a net where the animals and debris are retained while the water, air and very fine substrate escape. These techniques are used over a set area, eg the area of a cylinder that is placed on the substratum, to ensure they are quantitative. They are generally used in fine substrates within shallow static or slow-moving water where flow-dependent samplers such as the Surber sampler become inefficient.

Colonisation samplers provide an artificial substrate for invertebrates to colonise. Many patterns of colonisation sampler have been described but most are designed to provide interstices. Some designs simulate a natural gravel bed, while others are intended to mimic water weeds. Samplers may be embedded in the substratum, rested upon it or suspended in mid-water. The rationale behind the development of artificial colonisers was to 1) provide a uniform sampling area and thus improve the scope for statistical inference from data; and 2) overcome differences found with active sampling techniques attributable to the varying abilities of operators. However, the representativeness of communities that colonise artificial substrates to those found in natural substrates and the ecological significance of these communities has been debated (Hellawell 1986). For example, ***eriss*** has successfully used gravel-filled mesh baskets in a rocky stream (Rockhole Mine Creek) to standardise sample size. Use of similar colonisation samplers in the sand beds of Magela Creek were unsuccessful because colonising fauna was unrepresentative of that found in sand beds (C. Humphrey, pers comm).

4 Factors that influence the choice of sampling technique

As is apparent in the previous description of sampling techniques, two of the crucial factors in deciding which technique is to be used for collection of macroinvertebrates are whether qualitative or quantitative samples are required (which will be related to objectives) and what type of habitat is to be sampled. In this instance important features of the habitat include whether it is a flowing (lotic) or non-flowing (lentic) environment, what the substratum consists of (particle size, amount of vegetation) and depth. Another consideration may be the efficacy of different methods, ie the extent to which they may introduce bias by recovering certain organisms more readily than others and the degree to which fauna is separated from habitat material.

Tropical wetland environments can be difficult to sample quantitatively. This is particularly so for deeper, highly vegetated areas such as those found in billabongs and floodplains. Extracting animals from a defined area of these complex habitats is difficult without also collecting large amounts of vegetation (and thus increasing sample processing time) and preventing escape of more mobile taxa. Another difficulty with quantitative sampling is that techniques usually only cover a small area of substratum so the problem becomes how many sampling units are necessary to ensure that the sample includes most of the species present (Elliott 1977).

5 Qualitative versus quantitative sample processing

In this instance sample processing is defined as procedures used to extract animals from other material such as organic debris and sediment that may be collected in sampling. Most sampling techniques (with the possible exception of drift nets in certain environments) recover a range of material in addition to the desired invertebrates. The amount of excess material will depend on the habitat and the technique. If a quantitative sampling technique is used it is likely that quantitative processing will take place. Quantitative processing of semi-quantitative samples will allow comparison of rank abundances of species (ie abundance of species relative to each other will be known but absolute abundance for a defined area will not). Qualitative sampling probably only justifies qualitative processing.

Samples that are to be quantitatively processed require preservation after collection. Samples are then sorted through systematically at an appropriate level of magnification (generally 10x using a stereo microscope) to pick out the invertebrates for later identification. This procedure is necessary to ensure accurate enumeration and identification when there are large quantities of detritus in the sample. Samples from habitats with small amounts of detritus (eg sand habitats) may not require processing. For samples with high numbers of animals a sub-sampling technique is often used to reduce the time and effort required for processing. A range of subsamplers exist, but one needs to be chosen that will give subsamples representative of the whole sample. Results from subsamples can then be multiplied to give whole sample estimates.

A common approach to qualitative sample processing is live sorting. This procedure involves picking invertebrates out of the sample while they are still alive and only preserving those specimens. This procedure generally takes place in the field where samples are placed in a tray for sorting without any magnification aid. Standardisation of effort can be via setting a finite time period for live sorting (generally 30–60 min) or by defining the number of animals to be retrieved. These techniques result in greater time spent during sampling but less time spent in the laboratory. Problems in using qualitative processing techniques in tropical wetland systems include inclement weather and remote sampling locations which may result in a delay between collection and processing.

The relative merits of qualitative versus quantitative sample processing are similar to those described previously for sampling techniques (section 2). Qualitative processing has become more popular in recent times as part of efforts to reduce time and cost in assessing environmental conditions at a site and for use in broad scale studies where sampling of many sites is required for quick information turnover to managers (Resh & Jackson 1993). Quantitative processing techniques for samples from vegetated tropical wetland habitats can be very time consuming with recovery of 200 animals being known to take over a day (personal observation). Work done recently at ***eriss***, however, suggests that there can be high variability in recovery of rank order abundance using live sort techniques (Thurtell 1996, unpub). Further work may be required in tropical wetland habitats to determine processing methods that give consistent but timely results.

6 'Rapid Biological Assessment Techniques' – an example of qualitative sampling and processing

There are two objectives to rapid assessment: 1) reduced cost and effort (relative to quantitative sampling; and 2) to summarise the results of site surveys in a way that can be understood by nonspecialists such as managers, other decision-makers and the concerned public. Efforts to reduce costs must not be carried to the point that information used in the analysis does not adequately represent the site examined. Likewise the analysis and summarisation should not be so simplified that impact-related conditions are not detected. (Resh & Jackson 1993).

In Australia a nationwide biological monitoring program (the Monitoring River Health Initiative) is currently underway, based primarily on rapid assessment of benthic macroinvertebrates. Models derived from this program will be used to assess biological responses to water quality and/or habitat changes in rivers. Qualitative sampling techniques in a variety of habitats are followed by picking of live organisms on site. Sampling is standardised by area sampled, eg 10 m sweep along river edge, while sorting is time standardised: live sort for 30 min. Animals are identified in the laboratory to family level (Davies 1994).

7 Conclusion

Invertebrate survey involves the collection of specimens (sampling) and separation of specimens from associated detritus prior to counting and identification (sorting). A range of techniques from quantitative to qualitative exist for both sampling and sorting. The choice of technique will depend on the objectives of the study, the nature of the system to be sampled and available resources. Highly vegetated tropical wetland systems can be difficult to sample quantitatively.

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Survey techniques for fish

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Abstract

Fish survey may be used to assess and manage biodiversity, to study the ecology and ecosystem of the fish species, and/or to manage harvesting. The information obtained from a sampling program provides measures of fish abundance that may be qualitative, semi-quantitative and sometimes quantitative. A measure of fish abundance may be added to data on size and age distribution, fecundity and fishing effort, in order to model population dynamics and evaluate effects of harvest. There are many fish sampling techniques, and a method should be chosen according to the objectives of the study and the effectiveness of the technique in the environment concerned. Here a number of fish survey techniques are described, with comments upon their effectiveness in the Alligator Rivers Region, Northern Territory.

Keywords: Fish survey, sampling techniques, harvest management

1 Introduction

Surveys of fish are generally directed at one of three distinct objectives: assessment and management of biodiversity, studies of the ecology of fish and their ecosystem, or management of harvesting. Whilst similar capture procedures may be used for all, the different objectives, by and large, require different information from the surveys. There is, of course, a wide range of techniques used for fish capture and it is important to understand their advantages and limitations to judge which are appropriate. The very mobile nature of fish poses some different problems to invertebrates in the design of surveys. For example, when fish may range over a large area each day, how far apart do sites need to be to be considered as independent replicates and, indeed can sites ever be considered truly independent? Nevertheless, the large size and relatively low diversity of freshwater fish makes them easier to identify by comparison to invertebrates. This makes it possible to obtain biodiversity data rapidly so that fish are potentially useful for environmental monitoring as well as their other values. On the downside, representative samples of fish communities are much more expensive in terms of field-time than invertebrate samples.

2 Biodiversity survey

In biodiversity surveys the task is usually to establish the species present in an area or specific habitat type and, often, to quantify their abundance in a manner that can be easily repeated in the future in a monitoring program. Thus, the information obtained can vary from qualitative to quantitative. The measure of abundance of each species captured can relate to either the number of fish or their biomass, and often both.

For some purposes the presence or absence of different species is sufficient information. This can be quantified as frequency of occurrence data to indicate the rarity or commonness of a species. Simple ranks of abundance may be recorded if semi-quantitative data are appropriate. These strategies are often used in the comparison of community structure although quantitative data are also appropriate.

3 Ecological studies

In studies of ecological processes more quantitative data are usually necessary and the data recorded then may be the number and biomass of fish of each species per sample. Preferably the sample unit should relate to some measured quantity of habitat. In many surveys the length and weight of each individual is measured and samples of scales, otoliths or spines may be removed for age analysis if required. When very large numbers of fish are involved such measurements are only made on a sub-sample.

When it is not important to return fish alive, much other information can be obtained from fish specimens. Common variables measured include gut contents for diet analysis, gonads for development stage analysis and fecundity estimates, liver condition, fat deposit condition. Blood samples and indicators of the incidence of disease and parasite attack may also be examined to assess the health status of fish.

In all surveys measurements of environmental correlates and appropriate spatial data should be recorded.

4 Harvest management

In fisheries management research the data on the fish in question are always in some quantitative form, usually semi-quantitative. Where there is a fishery (commercial, subsistence or recreational) there is the possibility of obtaining data on catch per unit fishing effort (CPUE) from fishermen. This data can provide a measure of fish abundance and, combined with information on size and age distribution and fecundity obtained by biologists, and other information on fishing effort, provides the information required for modelling population dynamics and evaluating effects of harvesting. In many cases only a few, or often only one, species are examined in a study. Where multiple species catches are involved the population dynamics of each species may have to be examined separately.

Measurement of fish age is a specialised task requiring lots of tedious work. Also, the mathematics of population dynamics is complex and is a task more appropriate for specialists in this field.

When a source of fish catch data from fishermen is either not available or unsuitable for various reasons, it is necessary for biologists to obtain their own measures of fish population size and specimens for other data. Many methods of fish sampling have been developed for different situations and species. Again it is useful to separate the methods into semi-quantitative and quantitative measures of abundance. Semi-quantitative measures are those that can only yield catch per unit effort data while quantitative methods yield data on density (numbers per unit area, or volume, of habitat). The advantage of quantitative measures is that data obtained by different procedures can easily be compared with one another by adjusting to common units. *Semi-quantitative data can only be validly compared with data obtained by the same, preferably identical, procedure.*

In general, catches of fish made by passive procedures, such as traps and gill nets, provide only CPUE data. Catches made by active procedures, such as seine nets and electrofishing, can provide absolute density measures if a known area is fished. Mark and recapture methods provide estimates of total population size that could also be expressed as a density measure if the total area of water inhabited by the population is known.

5 Appropriate sampling procedures

Very often in freshwaters, the waterbodies being examined may not be very large and the resident fish population may be similarly small, especially if it is a large species. Killing of the catch, therefore, could have a significant effect on the size of that local population. This may have unfortunate effects on your inferences from repeat sampling if this was not already considered. In that situation it is appropriate to return as many fish to the water unharmed and the method chosen should be one that makes this possible.

Some of the more common sampling methods are outlined here.

It should also be noted that survey/research work on fish may require approval of animal experimentation ethics committees associated with different research organisations. The guidelines provided by these committees should be consulted when planning sampling and fish handling procedures.

5.1 Gill nets

These comprise a wall of netting (usually nylon) suspended by floats and weighted on the bottom. The nets must be anchored in place – an interesting exercise in strong currents. Fish catch themselves by swimming into the net and entangling their spines and operculae with the mesh. The size of the mesh dictates the size of the fish caught. Consequently, for research purposes a range of mesh sizes is used to capture the range of fish sizes of interest. Note that commercial fishermen are usually highly restricted in the mesh sizes they can use and this must be recognised when using their catch data. Commercial barramundi fishermen use gill nets.

Gill nets work well for larger and scaly fish. They work less well for smooth scale-less fish and very poorly for very small fish.

This passive procedure provides only CPUE data. However, if a large area is enclosed by fine mesh and subjected to repeated fishing with records of catch taken at fixed intervals, gill nets can provide an estimate of total abundance in the enclosure area from the rate of decline in the catch. This is termed a trap-out procedure.

A major disadvantage of gill nets is that the fish will die if not released soon after entanglement. This can be minimised by 'running' the nets continuously.

A gill net catch decline procedure, with continuous net running to minimise mortality, is used by NT DPIF for their barramundi survey work on Corroboree Billabong on the Mary River and on Yellow Water in Kakadu National Park.

5.2 Seine nets

These are sometimes called haul nets or beach seines. A seine comprises a length of netting (usually multi-filament) with a float line and a weighted bottom 'lead' line attached. The net is set so as to encircle an area containing fish and is then 'beached' by hauling it to shore by both ends. The fish are then gathered by hand.

Mesh size is important. Larger mesh sizes can be moved through the water faster and hence are more effective for catching larger and faster fish. However, small fish may pass through the larger mesh. Two or more nets with different mesh sizes may be used to overcome this problem if all sizes of fish are required. A compromise single mesh size is often used in survey work and stretched mesh of 5–10 mm is quite useful for this. Very fine mesh of 1–2 mm maybe necessary to catch very small sizes of fish but these filter water very slowly and most large fish escape.

Seine nets are difficult to use on a rough bottom with logs and boulders and in dense vegetation they will roll up and allow all fish to escape. They are therefore best suited to open water with a clear bottom but a necessary tool in any fish survey.

5.3 Fish traps

These generally comprise of a square or round box of mesh with a funnel entrance at one or both ends. They are placed on the bottom and fish swim into them either by accident or attracted by bait inside. Once inside the funnel makes it more difficult for them to get out.

The composition of the catch in baited traps is obviously influenced by the type of bait used. Unbaited traps avoid this problem, but all traps are somewhat selective in the species that will use them. Often wings of netting are attached to the front of traps to direct fish towards their entrance. Fyke nets are a design commonly used in fish research. These have at least two sets of funnels inside the cage to reduce escapement.

5.4 Electrofishing

This is done with devices that pass electric currents through the water to either stun the fish temporarily or direct them to swim towards a net. The cathode is usually left in the water and the anode is usually a collecting net.

In AC operation the electric pulse usually stuns the fish which must then be collected quickly in the net before they sink or revive and disappear. This shocking procedure (electronarcosis) requires good visibility and preferably shallow water. The pulse strength and frequency affects the size of fish stunned.

In DC operation the fish are induced swim towards the anode by the pulsed current (galvanotaxis). This method is useful in muddy water and in vegetation. DC units use a much stronger current than AC and are potentially more dangerous.

Experiments with the use of electrofishers in wetlands in the Alligator Rivers Region many years ago found them to be ineffective in the very low conductivity waters present much of the year. However, NTDPIF use an AC unit on a boat for collecting specimens of barramundi in billabongs for special purposes but not for population size estimation.

5.5 Pop-net traps

Popnets are traps designed to obtain quantitative measurement of fish density in dense vegetation. They are very much a research/monitoring tool although I saw a report of a similar procedure being used to catch fish in reed swamps on the Nile River in Africa.

Pop-nets are essentially a square enclosure of netting with a float frame at the top and a weighted frame at the bottom. The trap is set by inserting the net into the vegetation so that it rests on the bottom and there is a narrow passage through the vegetation for the net to extend to the surface. The top and bottom are then bound together by a trigger-strap so it all sits on the bottom. In this folded condition the trap is left for some time to allow fish to re-establish themselves in the area after the disturbance. The net is then triggered by pulling a rope, it rises to the surface enclosing the fish and then the work of extracting the fish begins. The vegetation is removed by hand and then the area is fished with a small seine net to catch all the fish enclosed. Seining is repeated until no more fish are captured.

The disadvantages are exposure to leeches and crocodiles. The former can be overcome, but the latter is more problematic!

eriss uses this procedure in shallow lowland billabongs that were sampled in the past, prior to the removal of buffalo, by gill netting and seine netting. The vegetation is now too dense for seining and the area of open water for gill netting greatly reduced.

A related technique is called a Drop net. These devices quickly drop down through vegetation to enclose the fish that are then obtained in similar manner. A variation of the traditional cast net.

5.6 Visual census

Where water clarity is good enough, visual counting of fish from either above the water or, where crocodiles allow, within the water is a very useful sampling technique that does no damage to the fish at all. It is widely used in the sea for reef fish surveys. In freshwaters fish observation from above the water is greatly facilitated by polarised sunglasses (preferably amber colour). It is possible to make both semi-quantitative and quantitative density estimates by variations of technique. As with bird watching, learning to recognise different fish species requires knowledge of the fauna and experience in the procedure before sampling. It is probably less biased than other procedures in terms of fish size and species detected (table 1) but differences between observers can be a problem.

In the Top End visual techniques are most appropriate in the clear headwater reaches. In the lowland reaches they are only suitable very early in the Dry season when water clarity is greatest. At ***eriss*** we routinely use visual techniques for monitoring. These include counting migrating fish from the bank and counting fish in channel billabongs from a clear-fronted canoe. We have also used visual counts of fish in fixed quadrats or along measured lengths of stream from the bank in small shallow streams.

5.7 Video

Like the visual census outlined above, opportunities for use of video are limited by water clarity that is very poor in freshwaters by comparison to the sea.

5.8 Sonar

Sonar devices are used extensively in large lakes and marine waters for locating schools and individual large fish. Such information requires a lot of calibration to be of use in survey or population studies.

They are commonly used for counting migrating salmon.

5.9 Poisons

Plant toxins are widely used in Aboriginal fishing (Bishop et al 1982). Rotenone, a derivative from derris roots used in Polynesia, has been widely used by scientists for sampling fish. It has the disadvantage of killing everything but it can be neutralised with potassium permanganate to restrict its area of action. Its use is more common in marine situations (rock/reef pools etc).

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Table 1. Comparison of fish numbers detected by gill-netting, seine-netting, and visual, bank-side count methods in the upper reaches of Jim Jim Creek, Kakadu National Park in 1996.

Scientific Name	Gill-netting	Seine-netting	Visual count*
Neosilurus ater	92	0	25
Nematalosa erebi	76	0	6
Syncomistes butleri	24	0	35
Megalops cyprinoides	29	0	0
Scleropages jardini	27	0	0
Anodontiglanis dahli	25	0	44
Neosiluris hyrtlii	22	0	5
Hephaestus fuliginosus	5	0	38
Arius leptaspis	4	0	0
Lates calcarifer	3	0	11
Toxotes chatareus	4	0	0
Arius midgleyi	1	0	0
Pingalla midgleyi	64	2	45
Leiopotherapon unicolor	45	5	28
Amniataba percoides	122	17	45
Strongylura kreffti	23	1	2
Ambassis macleayi	8	5	0
Glossamia aprion	5	1	1
Melanotaenia splendida inornata	62	375	289
Craterocephalus marianae	0	2367	439
Melanotaenia nigrans	0	343	106
Craterocephalus stercusmuscarum	0	253	267
Ambassis agrammus	0	34	24
Glossogobius giuris	0	18	0
Mogurnda mogurnda	0	3	1
Pseudomugil gertrudae	0	3	7
Denariusa bandata	0	0	1
Total No. of Species	**19**	**14**	**20**

*only made before road opened

Field exercise with fish

Four sampling techniques will be demonstrated: visual census, gill nets, minnow traps and pop-net traps.

The visual census will be undertaken at Barramundi Falls. An instructor will issue students with polaroid glasses and then show students the different fish that can be seen by mooching along the bank. They will then be shown a quadrat method of estimating fish abundance. If time permits a bankside transect will be done and students can try snorkelling to get a better view of the fish. Students should keep records of the species detected and their abundance for comparison with catches made at different location by nets and traps.

Gill nets and pop nets will be demonstrated at Corndorl Billabong. The pop nets will be set early in the morning. On arrival at the billabong after the morning lectures a gill net will be set and then the pop nets triggered. Clearance of the pop nets and 'running' the gill nets will then be undertaken. Students should record the numbers of each fish species captured by the two methods. Comparison of the list of species obtained by the three methods should show very different assemblages. Students will be asked to consider what inferences can be made from this.

Vegetation survey methods

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1 Introduction

Most general discourses on vegetation survey and design deal primarily with terrestrial habitats. Wetland environments present a particular set of challenges to surveying and sampling vegetation communities. In the Alligator Rivers Region, the dynamics of wetland systems are also heavily influenced by seasonal factors characteristic of the Wet-Dry tropics. Hydrological processes associated with the seasonal inundation of the wetlands are a major determinant of vegetation community composition. At a given point plant communities change with seasonal wetting and drying cycles, as well as along some environmental gradients such as water depth. In describing vegetation patterns associated with such regimes, plant communities need to be defined temporally as well as spatially. This has implications for sampling methodology and design employed in addressing questions pertinent to the aims and objectives of wetland management.

In the ARR the objective of many vegetation surveys has been to characterise and map the wetland vegetation communities, particularly those associated with the Magela Creek floodplain, in order to assess the impact of mining disturbances. The overall approach has involved broad scale characterisation of the major vegetation communities by a variety of descriptive methods. These surveys have then provided a basis for and framework within which more detailed studies have been established using quantitative vegetation parameters.

2 Approaching the survey

Any vegetation study or survey is based on the description and examination of identifiable entities such as plant communities. Invariably analyses of data about these entities has to be derived from some kind of representative subsampling.

The manner and methods by which entities are recognised, defined and sampled depends on a number of things:

- the aims and objectives of the survey;
- the scale of the survey;
- the type of vegetation being studied;
- the type of analyses that will be applied to the data;
- compromises and trade-offs that must be made for logistic and financial reasons.

Approaches to arranging sampling according to recognised vegetation entities vary in their objectivity. Subjective approaches may be expedient but rely on adequate reconnaissance and familiarity with the vegetation. When use of some kind of probability statistic is anticipated, more objective approaches involving random sampling regimes are necessary. However the level of sampling intensity required by these approaches to reveal the more obvious vegetation entities apparent from subjective reconnaissance may not warrant their use. (Mueller-Dombois et al 1974). It is important to acknowledge that for any given method there will be some level of subjective judgement involved. For large scale or reconnaissance vegetation surveys the purpose is often to detect and obtain a description of vegetation pattern and classification. This differs from the usual purpose of smaller scale statistical surveys, which is to determine an unbiased estimate of the mean for some variable of the populationor community as a whole.

2.1 Non parametric methods for vegetation classification

Clustering and ordination are the nonparametric techniques most frequently used in vegetation community classification. Large data sets can be simplified and condensed to reveal underlying pattern.

Cluster analysis aims to find natural groups, such that samples within a group are more similar than those in different groups. However, the clusters are artificial and may be unrealistic in situations where communities intergrade with one another.

In a study of the Magela floodplain communities Sanderson et al (1983) produced a classification of the herbaceous aquatic vegetation, the detailed categories of which were not reproducible in subsequent Wet seasons. However, discriminating at a higher order of dissimilarity resulted in fewer, broader, but more realistic vegetation categories that appeared to be consistent over several Wet seasons.

Ordination techniques preserve continuity and intergradation between samples by arranging sampling units along one or more axes that represent the effects of combinations of variables. The relative positions of the sampling units in the ordination space indicate ecological similarities and differences. By correlating environmental data with the ordination coordinates, it is often possible to identify correlated (and possibly causal) factors, eg community groups may be identified through a correlation with water depth or period of inundation.

3 Vegetation community sampling

In general four major steps need to be considered when approaching vegetation sampling

1. stratification or recognition of vegetation entities or communities.
2. selection of a sample plot within these communities.
3. size,shape and number of sample sites.
4. selection of estimate parameter/s to record from the sample sites.

3.1 Homogeneity

Homogeneity is held to be an important consideration in selecting an area as being representative of a vegetation community in which sample plots are to be located, ie:

- The sample plot should be large enough to contain all species belonging to the plant community;
- the habitat represented should be uniform within the sampling plot;
- plant cover should be as homogeneous as possible.

Lack of homogeneity compromises the validity of a recorded vegetation parameter or statistic as a meaningful average for the sampled area.

Attempts have been made to objectify the identification of homogeneity butit often remains a matter of subjective judgement through observation and familiarity with the vegetation.

3.2 Defining sample plot area

An area or plot, within which subsampling is to occur, thus needs to be defined with respect to its adequate representation of a given community species composition. Here the minimal area concept may be a useful guide, ie the smallest area in which the species composition of a given community is adequately represented. Basically, the larger the area the more species will be encountered, up to a point where no further new species are encountered.

In ideal circumstances this can be determined by a series of nested quadrats within each of which species presence is recorded. The resultant plot of species number against quadrat size produces a curve characteristic for a given community. At some point of levelling off along the curve a decision is made with respect to the effective representation of species composition for that community against manageable plot size, which ideally should never be smaller than the minimal area. In reality, plot sizes are often set intuitivelythrough previous experience with community types, ie tree dominated communities require much larger sample plots than small annual herb communities. Often plot dimensions for broad vegetation structure classes have been established through other studies and serve as a useful guide.

3.3 Quantitative vegetation parameters

The quantitative vegetation estimate parameters most often used in community sampling are:

- Frequency (presence/absence) – number of times a given species is recorded as present in a given number of quadrats or at given number of sample points within a sample plot;
- cover (crown, foliage, shoot, basal area) – usually expressed as percentage of the sample quadrat area;
- density – number of individuals of each species per unit area;
- biomass – the amount of living matter per unit area.

Frequency, in contrast to the other parameters, is an objective but non absolute measure – results are influenced by sampling frame or quadrat size and shape, and as such have most meaning in relation to that particular size and shape selected. No counting is involved, frequency being a recording of species presence only. This has the advantage of being potentially quick and easy to record. Frequency is, however, affected by the spatial distribution of plant species, ie the degree of dispersion or clumping, and this makes optimum quadrat size difficult to settle on. Low frequency values may arise from patchy concentrations of individuals with evenly spread individuals giving high values. This effect of non randomness has implications when relating frequency to abundance values such as density and biomass. Density estimates require that an individual plant can be identified, which may be difficult for many wetland species as these often form clonal entities of indeterminate origin. Biomass may be quantified indirectly (eg by cover and basal area) for terrestrial phases and some emergent phases of wetland plant species; otherwise, sampling is usually destructive, ie the sample is physically separated and removed from the sample site. Destructive sampling also requires care in its application so as not to constitute a disturbance in itself that may influence subsequent sampling. Generally a destructively sampled site can only be sampled once (unless, perhaps, in an experimental situation where vegetation removal is the variable being studied). Thus nested quadrat sampling methods which are less affected by quadrat size and spatial dispersion, and produce closer approximations to density values can be useful, in that they are expedient, do not require individuals to be defined, and are non destructive (Morrison et al 1995).

However, surface or emergent vegetation in flooded habitats will not always be a reliable estimate of the submergent fraction. Studies such as those that aim to relate to fish habitat may demand characterisation of vegetation in the water column. The main valid approach in this case is through destructive biomass harvests. These are time consuming and physically demanding, as well as presenting a challenge to identifying and quantifying the more tangled masses of unattached submergents. Bailey et al (1983), in a study on seasonal distribution of aquatic macrophytes biomass in Corndorl billabong, took total biomass estimates from water column samples and calculated dry weights from dried subsamples of the quadrat mass wet weight. No attempt, however, was made to differentiate species.

3.4 Sample quadrat dimensions

There is some argument over methods for determining optimum quadrat size within a sampling plot. Usefulness of the minimal area/species area curve principle has been debated (Mueller-Dombois 1974), but its applicability is dependent on what is considered to represent the most important function of plant distribution. In some cases this may be the distribution of the quantity of plant material (ie biomass) rather than the distribution of individuals. It is argued that this has little to do with the value of the species area curve as an indication of the representative species composition of the community. Where species diversity is considered the most important aspect of plant distribution, the species area curve is a useful tool for determining the smallest sample area with a maximum number of species for a community.

In practice, a number of quadrat sizes (usually nested) are laid out and replicated within a vegetation community plot, and examined for some index of variability. Sanderson et al (1983) determined by this method, over a number of different vegetation types, that $4m^2$ was a suitable minimum area for sampling cover estimates from random and transect orientated quadrats. However, for the clumped distribution of large floating leaved species, $10m^2$ was considered more appropriate to use.

In Sanderson's study, biomass harvests were conducted separately, with sampling sites based on communities defined in the earlier cover estimate survey. Macrophytes were cleared from $0.84m^2$ quadrats and sorted into species. Wet weights were taken for each species, and average dry weights of all species combined and expressed per m^2 for each vegetation type.

Bailey et al (1983) combined both visual observations of species composition and direct sampling of biomass along a fixed transect. Quadrat size was somewhat loosely defined in terms of visual observations of relative species composition (approximate percentage contribution by each species to the biomass of the community), made every 5m along the transect. Biomass samples were collected every 20–50m using $0.25m^2$ or $4m^2$ quadrats, depending on water depth and plant communities. The former quadrat size was considered more appropriate to floodplain areas of depth less than 30cm, whereas the larger quadrat size was chosen primarily to address the edge effects associated with the difficulty in cutting thick matting submergent grasses on the quadrat perimeter. In effect, combining visual and physical biomass estimates may provide an opportunity to assess the congruency of the two measures, such that the visual method could represent an acceptable and more expedient approximation of the latter, given the relationship is consistent. While such sample estimate relationships may be cost effective, save time and allow greater numbers of samples to be obtained more readily, they may not hold where the nature of the sampled community changes and thus need to be checked and reviewed appropriately.

Knerr (1998) and Finlayson (1989), in comparable studies on Magela floodplain vegetation communities, combined a variety of broad descriptive methods with specific transect sampling methods. Knerr sampled quadrats located both opportunistically and along fixed transects established by previous sediment seedbank sampling studies. In both cases, a concentrically nested quadrat method, as outlined by Morrison et al (1995), was used for recording frequency estimates in four major grassland communities. Quadrat dimensions are shown in figure 1.

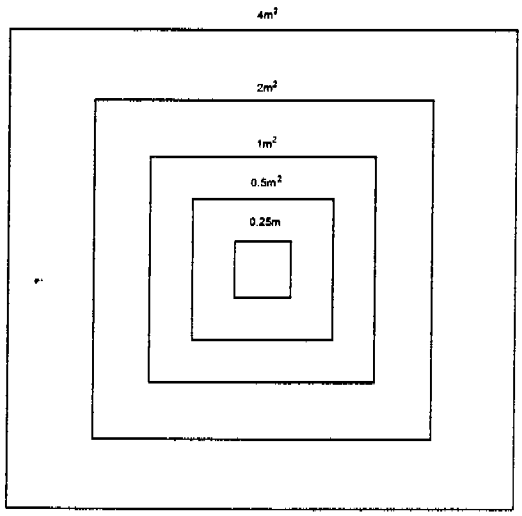

Figure 1 Arrangement of sub-quadrats in each nested quadrat used to survey *Brachiaria* grassland, *Hymenachne* grassland, *Oryza* grassland and *Pseudoraphis* grassland communities on the Magela2 floodplain (1995-96).

Knerr also used the same nested quadrat layout to determine optimum dimensions for flowering culm counts (essentially a density estimate) of dominant species in major grassland communities for seed production estimates.

By calculating the coefficient of variation of the total number of flowering culms within all nests of each species, optimum quadrat size was determined. Plotting the coefficient of variation against cumulative area suggested that quadrats larger than $1m^2$ were associated with little difference in coefficient of variance (figure 2), ie counting culms in quadrats larger $1m^2$ would be a waste of time and effort.

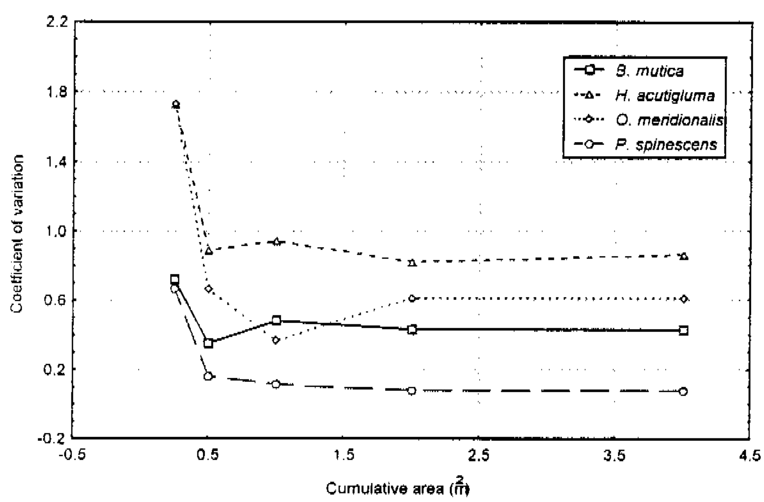

Fig 2 Coefficient of variation (standard deviation / mean) of the number of flowering culms recorded for each species with increasing sample area during peak biomass production in May 1996.

In general, a number of practical issues are associated with the use and selection of sample quadrat dimensions in wetland vegetation:

Defining an individual plant – amorphous indeterminate clonal masses are difficult to define as being in or out of a quadrat for density estimates (cover and biomass may be more appropriate parameters in this situation).

Edge effects – smaller quadrats, by virtue of having a larger perimeter to area ratio, may be subject to greater edge effects. Increasing the size of the quadrat will ameliorate this but the time and effort involved in data collection will be proportionately greater. Bailey et al (1983) found that in harvesting thick matting submergent grasses, the relative error due to peripheral omission or commission of material decreased with increasing quadrat size. The $4m^2$ sample size chosen represented a compromise between a manageable volume of plant material and an acceptable sampling error.

3.5 Determination of sample size

The number of sample points or quadrats that are required from a given sample plot needs to be determined; this is important where an estimate of the mean for some variable of a plant community, such as density, is required. There are a number of methods used to help define the optimum number of samples. One frequently used in vegetation sampling involves calculating the running or cumulative mean for some parameter of measurement for key species in a sample plot. As more quadrats are sampled, the variability in the running mean decreases to a point determined as an acceptable trade-off between accuracy and feasibility.

The number of plot replicates within a vegetation community also requires consideration. The configuration and number of sample plot replicates, as well as sample size, will influence the assessment of statistical variance and thus the outcome of subsequent analyses. How this issue is dealt with depends on the objective of the survey, particularly where environmental variability and changes in space and time are of concern.

Sampling intensity and precision need to be appropriate to the aims of the survey (Austin 1991). For instance, a study examining the effects of a fire event on a vegetation community may involve replicate sample plots within each of burnt and unburnt areas of the community, where each plot is characterised by a number of sample quadrats. Intensive sampling of many quadrats within few replicated sample plots may be statistically inadequate and ultimately a waste of effort. Similarly, if species richness (the number of species per unit area) is the relevant parameter for the aims of the survey, then the analytical advantages of larger sample sizes and sample plot replicates afforded by more easily collected nested frequency data may be greater than that of fewer, but more intensively collected, biomass harvest data. If, however, some precise measure of abundance, eg biomass, is more relevant to the aims of the survey, then the whole issue of sample size and replication has to be reappraised. Again there is a compromise between accuracy, acceptable error and feasibility.

3.6 Sample timing

As noted earlier, the seasonality of the wetland environment in the Wet-Dry tropics is a major controlling factor in the dynamics and composition of vegetation communities. In attempting to characterise vegetation communities over several years, Finlayson (1989) determined that those communities defined by sampling during peak biomass production periods appeared to be the most consistently represented between Wet seasons.

3.7 Transects

Line transects have featured prominently in most of the ARR wetland studies cited. The transect is a particularly appropriate way of configuring sample points when monitoring the dynamics of wetland vegetation communities over spatial and temporal gradients, such as water depth, floodwater dispersal and regression, as well as movement of free floating vegetation. The transect could be viewed as a long narrow sample plot, except that it may traverse vegetation community boundaries. As mentioned previously, Bailey et al (1983) exploited this aspect where community boundaries could not be easily defined. Transect length is usually a matter of subjective judgement based on inferred or discernible gradients, ie from the edge of a flood high-water-level through to a zone of permanent inundation. Assessment of the number, size and distribution of quadrats along the transect, as well as statistical arguments associated with replication, follows similar principles to those discussed previously. For temporal surveys, relocation of permanent transects is essential. Most simply, transect end points can be prominently marked (to be still visible above peak flood levels) or at least one end point (usually terrestrial) marked, from which an accurate compass bearing can be taken with which to lay out some kind of marked line (tape measure, rope with floats placed at measured intervals). Transect end points should always be georeferenced as accurately as possible. Physical markers can be inadvertently or deliberately removed or burnt, pushed over by animals, or simply the location forgotten.

3.8 Remote sensing

Finlayson et al (1989), Knerr (1998) and Sanderson et al (1983) all used remote sensing (aerial photography) as a basis for a regional definition of broad vegetation categories, and as an aid to preliminary stratification of sites for more detailed community sampling. The generation of vegetation maps in this way is often an iterative process, where initial interpretation is modified by subsequent surveys, the results of which, in turn, provide an increasingly accurate basis for further study.

Knerr also carried out a visual assessment of the dominant plant species at 1048 locations georeferenced during airboat reconnaissance. These points were used as a guide in identifying vegetation types defined in previous surveys by Finlayson, as well as assist in air photo interpretation of major grassland communities.

Georeferencing sample data points is essential in any vegetation survey, particularly where permanent sites must be revisited to monitor temporal changes. In addition such data has the potential to be entered into a GIS, providing opportunities for overlaying other data sets and attatching attributes.

4 Summary

Many of the vegetation surveys carried out over the ARR wetland systems have taken broadly similar approaches (Bailey et al 1983, Sanderson et al 1983, Finlayson et al 1989, Knerr 1998). All begin with a descriptive overview and attempt to establish a consistent description of principle vegetation communities. These then provide the basis for more detailed studies employing quantitative parameters.

Whether a survey is an essentially descriptive exercise, such as mapping vegetation communities, or interrogative and attempting to address some kind of hypothesis concerning causal relationships with environmental variables, in a less than ideal world, the challenge is to find an equitable trade-off between optimum sampling methodology and technical feasibility, while still addressing the fundamental aims and objectives of the survey.

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Survey techniques for hydrology, water quality and sediments

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Abstract

Survey techniques, whether for water or sediment quality, require that the objectives of the study be determined before sampling commences. If this is not done then the probability is high that useful information will not be obtained from the data, and the implied objectives of the project will not be met. Other planning requirements for successful project execution include: a comparative assessment of available resources and proposed needs; the establishment of data quality objectives; a benchmark to determine whether the objectives of the project have been met; and a detailed description of how the technical aspects of the project will be carried out. All these requirements are incorporated into a *sampling protocol*. These notes describe how a sampling protocol can be developed, and are tested using a *pilot study*, which also serves to allow an estimate to be made of variability of indicator concentrations within the project area. The notes also describe quality control and assurance methods for sample collection, transport and analysis; and how the final numerical database can be compared with an 'attainment benchmark' or 'success criterion', preceded, if necessary, by mathematical manipulation of the data.

Keywords: water quality, sediment, sampling, protocols, quality assurance

1 Water sampling

This lecture will provide an introduction to the design of water-sampling protocols, the collection of samples and the subsequent manipulation of data. For illustrative purposes, it will address the issues with particular reference to providing advice to users of the *Guidelines for Fresh and Marine Water Quality* (GWQ). These guidelines are largely based on toxicological data and are heavily oriented towards the ecological protection of wetlands. One focus of the guidelines is to provide guidance to users on consistent and uniformly applied surveying principles for the complete series of steps from project design to statistical evaluation.

1.1 Steps to acquiring data to compare with Guideline values

The task of acquiring data for comparison with the GWQ can be divided into eight discrete steps:

1. Assess the resources that you have available.
2. Define the temporal and spatial boundaries of the sampling problem.
3. Establish an attainment benchmark, which broadly means the proportion of measured values which must not exceed the guideline.

4. Design a sampling protocol that maximises the representivity of samples, and minimises that component of variance that is not relevant to the environmental value.

5. Collect the samples, with due regard to technical aspects of quality control and quality assurance.

6. Analyse the samples, with equal regard to quality control and quality assurance.

7. Determine the biologically available component of the physico-chemical indicator, either by using a speciation-specific method of analysis (eg ASV or some chromatographic techniques), or by submitting broad analytical data to a thermodynamic speciation model (such as MINTEQ or HARPHRQ).

8. Perform a statistical analysis on the data and compare with the attainment benchmark.

1.2 Definition of the sampling problem and its relationship to available resources

1.2.1 General issues in the design of protocols

The most important issues in the design of a sampling protocol for physico-chemical indicators are:

- to carefully determine the specific objectives of the study and the resources available
- to collect representative samples
- to manage variance

These issues are closely related. A careful assessment of the purpose of the study will usually suggest temporal and/or spatial constraints on sample acquisition, which will reduce the number of samples required, increase their representivity for the objectives defined, and minimise that component of variance that has little relevance to the relevant problem. These general issues are graphically illustrated by the decision tree below.

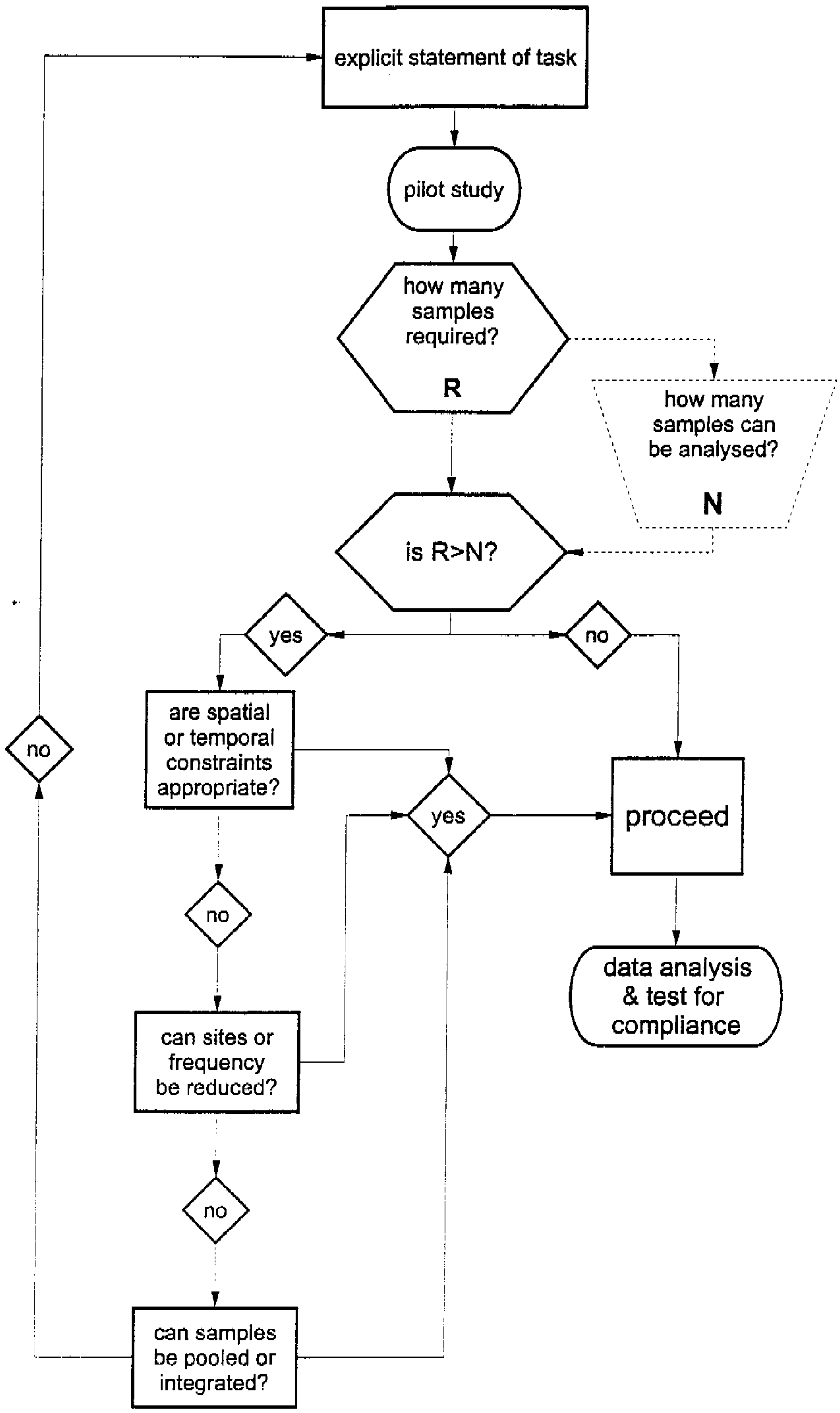

Figure 1: Decision tree for determining temporal and spatial constraints on sampling

1.3 Establishment of an 'attainment benchmark' and calculation of sampling intensity

1.3.1 General principles in assessing sampling intensity

Conceptually, more samples are required when:

- variability is greater
- measured values are closer to the guideline value
- the environmental value being protected is more important

These concepts can be expressed by the inequality:

$$\mathbf{G} > \{\mathbf{X} + [(\mathbf{s}/\sqrt{\mathbf{n}}) \times \mathbf{t}_{1-\alpha}] + \mathbf{z}_\beta \times \mathbf{s}\}$$

where **G** is the guideline value, **X** is the sample mean, **s** the sample standard deviation, **n** the number of samples, $\mathbf{t}_{1-\alpha}$ the value of the *t* distribution for (**n**-1) degrees of freedom and (one-tailed) degree of confidence required, and $\mathbf{z}_\beta$ the (one-tailed) value of the normal distribution for the frequency required.

Therefore, if the benchmark for comparison with a guideline value of 100 µg/L was 95% confidence that 95% of measured concentrations were less than this value, a sample dataset with **X** = 70 µg/L, **s** = 14 µg/L and **n** = 10 would yield a value for the right hand side of the expression of:

$$70+[(14/3.16) \times 1.833] + 1.645 \times 14$$

which equals 101.2, and the benchmark is not achieved. The expression is a sensitive function of **n** (assuming that $s \sim \sigma$) and this feature reduces the need for the guidelines to specify the number of samples required. A small number of samples can only satisfy this criterion when either:

- measured values are much smaller than the guideline value (in which case extensive sampling would be tedious and unproductive in any case)
- variance (and hence s) is small
- the environmental value has less importance, in which case the confidence with which a certain proportion of values are less than **G** could be relaxed, for example 50% confidence that 95% of values were less than the guideline value.

One advantage of this comparison benchmark is that progressive concentration data can be evaluated, and the monitoring exercise terminated or scaled down when the criterion is satisfied. This course of action must still accord with any temporal sampling requirements eg a need to monitor over an annual cycle may need to be complied with, even if guideline values were not exceeded using a three-month data set. However, sampling frequency may legitimately be able to be reduced.

1.3.2 Additional comments on sampling intensity

The value of the *t* statistic converges to that of a normal distribution for large **n**, and is only about 5% larger at n = 20. The collection of twenty samples would normally be regarded as an absolute minimum, regardless of apparent compliance with a smaller number. Note also that the statistical treatment described assumes an approximately normal distribution of data. Where data are markedly non-normal, approaches discussed later may be considered.

In a few cases guideline values are expressed in terms of an increase from a reference or otherwise specified value. In this case, the number of samples required is expressed by the equation:

$$\mathbf{n = 2s^2(z_\alpha + z_\beta)^2/d^2}$$

Where z_α and z_β are the upper critical points (ie one-tailed) of the normal distribution for the % confidence and frequency specified (for example 95%, 95%). The pronumeral **d** is the difference required to be observed. For example, if a 10 μg/L increase in an indicator concentration is the maximum allowable increase, with non-compliance judged by 95% confidence that 95% of observations exceed the critical value, and **s** = 14 μg/L, then the number of samples required is:

$$n = 2\times14^2\times(1.96+1.96)^2/10^2$$

$$\sim60$$

The use of z rather than *t* assumes a sample size large enough (>~20) to render the difference between the statistics insignificant, and this would typically be the case for this form of compliance monitoring. The equation above requires a value for **s**. This value can be determined either from an historical database (assuming that data acquisition methods and quality control are sufficiently consistent to permit valid comparison), or from a pilot study that is extensive and representative enough to give a good estimate of σ (the population standard deviation). Note that **d** can be expressed as a percentage if **s** is replaced by the relative standard deviation (coefficient of variation).

1.4 Representivity and indicator variance

A few hypothetical examples will help to clarify the general issue of representative sample collection, and its relationship to the problem of 'irrelevant variance'. In each case they involve the exercise of judgement in sampling, and an implied abandonment of a strictly random sampling protocol.

1.4.1 A stratified reservoir with outlet below the thermocline

In this case there would be little point in extensive sampling of surface water, except to determine the nature and extent of the stratification. Surface samples would not be representative of the outlet water, and would inappropriately increase the variance of sample concentrations. In addition, if for example water was drawn off once a week, there may be little point in sampling more frequently than this.

1.4.2 Water sampling in association with stream or lake macroinvertebrate monitoring

Where physico-chemical indicators are determined together with benthic macroinvertebrate sampling, water samples should be drawn from as close to the bed of the water body as possible, especially in water deeper than one metre, unless it was demonstrated through a pilot study that the water body has vertical homogeneity for the indicators being measured.

Surface samples would not necessarily be representative, and collection from a variety of depths may increase variance in a way that would not assist the objectives of the study.

1.4.3 Compliance monitoring of waste releases, or natural increases with disruptive events

Deterioration in water quality is often associated with predictable events, such as waste releases from industrial sites, or increases in indicator concentrations during storms. In these cases, sampling must be timed to coincide with the spatially and temporally relevant event.

1.5 Estimating the variability of the sampling area and optimising sample collection

Where a reliable historical database does not exist, an initial estimation of variance must be made using a pilot study. This is particularly important where a random sampling protocol is necessary, either because of prescribed requirements or because of an initial assumption that all potential sites are equivalent.

Where an entire catchment must be monitored, the location of sampling sites can best be optimised using graphical methods or the minimisation of a mathematical function, such as *simulated annealing*. Simulated annealing belongs to family of techniques (Dixon & Chiswell 1996) that 'spatially optimise' the selection of sites. This method requires a digital elevation map, and operates by minimising a *cost function*. For example, if sampling sites are required to be located at points of equal upstream drainage area, the cost function to be minimised would be the standard deviation of subcatchment areas. Similarly areas of equal discharge, total stream length, or some other parameter may be required, and the standard deviation of these would be minimised with the cost function.

At each site it may be possible to reduce the number of samples collected by integrating the collection or by pooling individual samples. Pooling or integration is usually performed in the dimension of least variance. For example, if a pilot study shows little vertical stratification but considerable variability along a transect, either *depth integration* or *pooling* may be considered. The latter technique allows the flexibility of retaining individual aliquots for later determination if data analysis indicates the necessity of performing additional analyses.

1.6 Other strategies to minimise unwanted variance

1.6.1 Filtration

Variance can be minimised by filtering the sample, assuming that this can be done without contamination, and that the indicator that you are measuring is not altered in the process. Filtration reduces variance because particulate components of natural waters are, in general, more heterogeneously distributed than soluble ones. Particulate phase components usually have low bioavailability and therefore have little relevance to the philosophy and mechanisms underlying the establishment of guideline values for the protection of ecosystems. This is because guideline values are usually established using soluble, highly bioavailable forms of toxicants. Unfiltered samples have the advantage of providing a 'safety margin' (that is, providing an upper limit of bioavailability). However, the magnitude of this safety margin cannot be quantified and in extreme cases can be several orders of magnitude. In any case, a safety margin is built into the derivation of guideline values. It should also be noted that thermodynamic speciation models have the greatest predictive power when solution-phase components only are included.

1.6.2 Mixing zones

Where industrial effluent is the issue of environmental concern, a mixing zone immediately adjacent to the site of release will usually be observed. This zone typically displays a high degree of spatial heterogeneity, which greatly increases the variance of concentration measurements. Such intense sampling rapidly consumes overall resources available for the project without necessarily increasing knowledge of the system to any meaningful extent. Unless sampling of the mixing zone is explicitly required under the terms of the monitoring, it should be avoided. In this latter case, an abridged suite of indicators which can be measured rapidly, such as those measured using specific ion electrodes (including pH), electrical conductivity and those amenable to in-field colorimetric determination (some nutrients) should be considered.

1.7 Quality control and quality assurance in the field setting

Quality control and quality assurance are different but related concepts. In the context of the guidelines:

> *Quality control means devising and implementing safeguards to minimise the corruption of data integrity.* These safeguards must be installed at every step of the process that leads from project definition to the decision on whether measured concentrations are in compliance with the guidelines.
>
> *Quality assurance means devising tests of whether the safeguards have been effective.*

Quality control in the acquisition of field samples has been comparatively neglected until recent times, and quality assurance arguably more so. This is probably the most important single reason why historical data sets should be viewed with caution. Explicitly,

The overall objective of quality control in the measurement of physico-chemical variables is the determination of the indicator concentration that existed at a specifically defined location and time immediately before the sample was taken. In most cases this requirement extends to the chemical speciation of the indicator.

Field activities are widely viewed as being relatively uncomplicated, and field operatives are frequently selected on the basis of qualities (for example vehicle-handling or bush skills) that have little relevance to the assurance of sample integrity. Field procedures are frequently regarded as being matters of common sense, and specific training in preparation and execution of sampling protocols as a misallocation of resources. In fact, the sequence of events from project conceptualisation and design, to the return of samples from the field is so complicated as to require:

- detailed planning and preparation
- elaborate safeguards
- rigorous training
- extensive acquisition of quality assurance samples.

The discussion below raises issues in planning and execution of a sampling protocol that may not be able to be resolved without implementing a 'dry run'. As noted above, the inclusion of a pilot study into the overall project plan not only yields crucial initial data, but also permits the identification and resolution of logistical and quality control deficiencies which could otherwise undermine the viability of the definitive project. The preparation of a sampling protocol should therefore be viewed as an iterative process. Many of the ideas below are summarised and paraphrased from Keith (1991).

1.7.1 Planning and preparation

The first step in any planning exercise for physico-chemical sampling is to determine any logistical and administrative constraints that may be placed on the exercise. These may include the availability of specialised sampling equipment, transport, staff who are appropriately trained, access to possible sites in the case of unusual meteorological events, and permission that may be required to visit sites. Evidence that these issues have been considered and resolved should be fully documented and incorporated in the formal sampling protocol.

Concurrently, or immediately afterwards, a complete list of analytes should be decided. This in turn mandates consideration of a number of inter-related quality control issues such as:

- is analytical equipment of sufficient sensitivity, and are support services and appropriately trained staff available?
- what type of collection vessels and preservation techniques are required for the analytes? For multi-indicator studies this will require the construction of a matrix in most cases. For example, samples for heavy metal and organic carbon determination require plastic and glass containers respectively. Samples for heavy metals are usually preserved with acid, which is inappropriate for nutrients, whereas biocides are inappropriate preservatives for heavy metals. Preservatives may interfere with the analytical method for indicators even if the preservative does not affect the analyte *per se*. In practice, this dislocation of sampling and preservation requirements may be the effective equivalent of collecting many more samples than a simple calculation would suggest, with potentially severe implications for sampling intensity.
- how will sampling equipment, including collection vessels, be cleaned and transported in an uncontaminated condition to and from sampling locations?
- what strategies will minimise contamination at the time of collection?
- to what extent can the integrity of samples be compromised and still satisfy the objectives of the project, and what can be done if the degree of compromise is too great? This consideration usually takes the form of formal 'data quality objectives' which are a type of continual quality assessment throughout the project, using field quality assurance samples (which are discussed in more detail below). Data quality objectives *must* be specified before a project starts, and describe what actions are to be taken if a failure of quality control is detected. Data quality objectives must be supported by sufficient quality assurance samples to allow the diagnosis of the source of quality failure.
- are there any resource or logistical bottlenecks at the laboratory that will cause processing delays that will undermine sample integrity?

Decisions on all these points need to be completely specified, and form part of the written sampling protocol.

Once sampling sites have been decided, their location must be accurately specified, preferably using a geographic positioning system. Where transects are sampled the location range should be specified if this is within the precision of the positioning instrument. The exact location of sampling sites and any subsites must be recorded in the sampling protocol. Taking note of the time when samples are taken is an obvious but frequently overlooked requirement of rigorous sample definition. Where automatic sampling devices are used, their timing mechanism must be calibrated to ensure that samples are acquired at the specified intervals. This is especially critical where hydrological or other conditions result in significant short-term concentration variations.

1.7.2 Some practical safeguards

- Sample containers and their caps should be soaked in at least 5% v/v acid for 24 hours unless special circumstances explicitly make this inappropriate. They should then be thoroughly rinsed with water, with the final rinse being with laboratory quality water. Soaking in a detergent solution is optional for most applications but is probably unwise for containers used for sampling organic compounds or nutrients. Glass containers should be heated in a muffle furnace at ~500°C for 20 minutes and stored dry. Plastic containers should be stored completely filled with high purity water.
- Sample containers should be transported to the field in sealed plastic bags, with a separate bag for each container type.
- Reagents for use in the field should likewise be stored in decontaminated containers and transported in separate sealed bags.
- All field equipment, such as filtration apparatus (including membranes), measuring devices and sampling equipment such as depth samplers must be cleaned before being transported in their separate receptacles. Elements of field equipment that will come in contact with samples after collection must be cleaned to the same standard as containers, as must other components which may contaminate contact elements during transport. The internal components of depth samplers, hand aspirators and tubing through which samples flow are often neglected in this regard.
- Containers filled with water should be emptied away from the immediate site of sampling, downstream if possible. Recap before submersion and thoroughly rinse with sample before taking the final volume.
- If taking samples from a flowing stream from a standing position, collection should be accomplished facing upstream. Similarly, if taken from a boat, collection should be from the bow with the boat facing upstream. Ideally, the sampling site should be approached from downstream.
- In still water, collect the sample away from the direction of approach.
- If taking samples by hand from beneath the surface, wear disposable gloves.
- 'Surface' samples should be taken from a few centimetres below the surface, unless you deliberately wish to bias your sample with the surface film. The container cap should not be removed until the container is submerged.
- 'Bottom' samples should be taken a few centimetres above the bed to avoid sediment contamination. A conscious attempt should be made to avoid disturbance of the bed during approach.
- Fill containers completely with sample and recap while submerged.
- Leave containers uncapped and out of their transport bags for the minimum time consistent with the recommendations above.
- Ensure that the chain of custody is fully documented. This means that the person responsible for each step in the sampling process is recorded.

- A field record of unusual meteorological or hydrological conditions, particular difficulties encountered during sampling, unexpected delays or other departures from normal circumstances should be made for possible later evaluation, together with the original records of any field measurement devices.

Explicit safeguards form part of the planning exercise and should be formally incorporated into the written sampling protocol.

1.7.3 Training

Training for field sampling has two aspects: competence in the technical requirements of the various tasks and a detailed knowledge of the requirements detailed in the sampling protocol. The first are generic skills that are in principle transferable between projects, and include the operation of equipment, field safety procedures and a general knowledge of quality control in the field setting. The second involve specific training in the particular requirements of the project. These may be largely issues of logistics, coordination, communication and project-specific aspects of quality control. Training to produce an intimate knowledge of a specific sampling protocol will clearly be facilitated by involving all those involved in the project in the detailed development of the protocol. This will also make it a more inclusive and authoritative document, as well as far more likely to be adhered to.

1.7.4 Quality assurance in the field

The inclusion of quality assurance samples in a sampling protocol is the only means of warranting that quality control procedures have been effective, and thereby satisfying data quality objectives. There are three main categories of quality assurance samples:

- field and trip blanks
- field and trip reference samples (samples of known concentration)
- replicate samples.

Field and trip blanks are samples that nominally contain none of the relevant indicator (though they may contain matrix species) that are taken to the field. They differ in that trip blanks stay in their transport container(s) (usually plastic bags) for the whole journey while field blanks are removed from their bags, usually opened at the sampling site, then returned. In principle, field blanks experience all manipulations that authentic samples do, except the physical removal of sample. They are therefore unable to detect contamination during the sampling process. Trip blanks do not directly experience the field environment, and are therefore useful as a diagnostic aid when contamination is detected in field blanks.

Field and trip reference samples are analogous to the corresponding blanks, except that they contain the analyte(s) at a known concentration. They convey more information than blanks because they can detect analyte loss (for example to the container walls) as well as contamination, but are less able to detect minor contamination.

Replicate samples are those that are taken, as far as possible, at exactly the same place and time as one another, which should result in them having nearly identical analyte concentrations (presumed variance of zero). Unless there are unusual circumstances no more than duplicate samples need to be taken. Their real value, apart from a direct indication of departure from consistency lies in their matrix equivalence with one another, something that can rarely be achieved with blanks or reference samples. They are also the only way that contamination or loss can be detected at the exact moment of sampling, and so perform the function of a diagnostic aid.

Quality assurance samples can detect both random and systematic errors. In practice, the latter can usually be detected with far fewer samples. This is because the effects of common systematic errors, such as inadequate container preparation, inappropriate containers and deficient transport arrangements will often be evident in most samples determined. In many cases, the magnitude of random errors can only be estimated by analysing a large number of quality assurance samples, more than can be accommodated within resource constraints. The best compromise to probably to take far more quality assurance samples than will likely be required to be analysed. The purpose of many quality assurance samples is diagnostic, that is, they sample a subset of all possible sources of failure of quality control. They are not analysed unless a problem is detected in samples that integrate a range of possible failures, or unless a more detailed investigation of random errors is required.

1.7.5 Recommended numbers of field quality assurance samples

At least duplicate trip blanks and reference samples should be obtained. These would usually not be determined unless quality control failure was detected in field blanks or reference samples, or in duplicate samples.

At least one, preferably duplicate, field blanks and reference samples should be prepared at each sampling site. Normally one of each would be determined.

Replicate samples should be taken for at least one in five unique samples; if logistics permit, one in three is preferable. Unique samples include all subsampling sites, including depth and transect samples. A minimum requirement for analysis in the absence of a demonstrated failure of quality control would be one replicate determined for every ten unique samples.

Although these recommendations may seem excessive and may reduce the number of unique samples that can be determined, there is no other way to provide evidence of the integrity of the samples collected, and hence the success of the sampling exercise.

1.8 Quality control and quality assurance in the laboratory setting

The importance of strict adherence to analytical protocols, and an appreciation of the critical relevance of rigorous quality control and assurance in the laboratory is far more thoroughly appreciated than in the field. Proper laboratory practice is codified in the requirements of registration authorities (such as the National Association of Testing Authorities) and any laboratory holding registration from these organisations will be familiar with the effort required to ensure a credibly performing facility.

Quality control in the laboratory depends on similar precepts to those applying in the field. These are:

- adherence to validated and clearly explained written methods
- sound training on a continuing basis
- proper documentation of all procedures.

Laboratory quality assurance relies on what can broadly be termed independent analytical comparisons, which include:

1.8.1 Blanks

Blanks should be incorporated at every step of sample processing and analysis. However, only those blanks which have been exposed to the complete sequence of steps within the laboratory will usually be determined unless contamination is detected in these. That is, blanks incorporated at intermediate steps are retained for diagnostic purposes only.

Blanks suffer the deficiency of being able to detect contamination only, not indicator loss. In this sense they are inferior to samples of known concentration. They are useful to detect minor contamination, where the superimposition of a small additional signal on a sample of known concentration may not be evident in the statistical evaluation of analytical data.

1.8.2 Samples of known analyte contents

Samples of known concentration may be placed into three main categories: reference samples that have been certified by a rigorous interlaboratory comparison and data analysis; control samples, which are defined here as materials that have been characterised in-house (and perhaps by a small number of additional laboratories); and unknown samples spiked with a known quantity of analyte.

1.8.3 Interlaboratory comparisons

Interlaboratory comparison of unknown samples is mostly useful for testing instrument calibration, performance and operator skills, and these programs are frequently sponsored by testing authorities. Generally only a modest degree of sample preparation is required, presumably to restrict the range of sources of variance between laboratories.

A more thorough interlaboratory comparison can sometimes be arranged when more than one organisation is involved in the project concerned. In this case the comparison can encompass every step of the sampling, preparative and analysis exercise.

1.8.4 Use of alternative analytical methods

Where a laboratory has access to alternative means of determining a specified analyte, many of the uncertainties regarding the speciation of analytes, speciation behaviour of spikes and the rate of approach to equilibrium can be resolved. This presupposes that at least some of the methods give specific information on the chemical environment of the analyte.

1.9 The relevance of chemical speciation to environmental values

Chemical speciation (the form in which the chemical indicator is present) assumes critical importance where the environmental value concerns ecosystem protection or human health. One problem is determining the chemical form of indicators. Another is deciding which species make a contribution to effects on the environmental value.

In the past, total (that is, unfiltered) concentrations were measured and compared with guideline values, on the understanding that this approach probably overestimates the amount of indicator available to cause detriment to the environmental value. A refinement to this approach is to measure total filtered concentrations. This is a conservative approach (though less so than using unfiltered samples) because the diversity of chemical forms in the solution may have different detrimental effects.

There are two approaches to resolving the 'speciation problem':

- determination of the indicator using an analytical method that is species specific
- use of 'thermodynamic speciation modelling'.

1.10 Statistical evaluation of data

After all analyses have been completed and validated, the product of the sampling and analysis project is an accumulation of multivariate physico-chemical concentration data. The possible sources of variability in these data are

- sampling error
- analytical error
- long range (that is, between site) variability
- short range (that is, subsite for example transect or depth) variability
- temporal variability

The ultimate task is to mathematically process these data in a way that will allow comparison with the guideline recommendation or other appropriate benchmark, which is usually in the form of a single concentration value, less commonly a range.

However, an assumption underlying the use of quantitative tools to compare data with benchmark values is that the data are normally distributed. As it happens, the probability calculation derived from the use of the *t* distribution is not very sensitive to departures from normality (Natrella 1963). However, an attempt should be made to normalise the data to the extent possible before an attempt is made to test for compliance with comparison values. The following manipulations may assist in normalising data.

1. Generally speaking, replicate values should be averaged. This assumes that sampling and analytical errors are small compared with between-site variability. This will usually be the case in the absence of a serious failure of quality control.
2. A test of normality can be made if desired using the reduced temporally and spatially distributed data set for each sampling site. Most spreadsheet programs will analyse data distribution in terms of departure from normality. If the data are satisfactorily distributed, a benchmarking comparison can be made. If not, data transformation will be necessary.
3. The most straightforward method of normalisation is data averaging (Natrella 1963). In the first instance, means should be taken of data in the dimension of smallest variance. For example, if transect and temporal data were acquired for a sampling site, but variance in the transect data was less than in the temporal data then the mean should be taken of transect data. This results in a reduced data set with a single concentration value for each sampling site for each sampling occasion. Normality could then be tested again, and if satisfactory a test for compliance performed.
4. If large departures from normality were still observed, then mathematical transformation of data is required. For environmental data, the most common transformation is logarithmic, which means that the logarithm of each concentration value is calculated (any base is appropriate, but base 10 and *e* are most commonly used). Other transformations that may be used include square root transformation and transformations using various trigonometric and hyperbolic functions. The transformed data are then tested for normality and if satisfactory, compliance tested, after the transformed mean and standard deviation are converted back to linear form.

2 Sediment sampling

When planning a sampling program for sediments, it is important to remember these are usually highly heterogeneous materials, with the indicators of interest usually present in a number of chemical forms. This typically means that the sediment, once dried, fractionated by size and homogenised must be subjected to several chemical manipulations, called sequential extractions. Sampling and preservation must take into account the requirements of each of these steps, as well as the normal requirements of avoiding contamination and loss.

Sediments usually have pronounced vertical gradients for most indicators of interest, so a program must take into account this three-dimensional sampling requirement.

2.1 Selection of sampling sites

It is important to remember that in most cases it will not be feasible to select many individual (that is, unique) sampling sites. This is because, as suggested above, the number of water samples for ultimate analysis proliferates quickly as a result of the interaction of vertical sampling and various sequential extractions. It is self-evident that if many subsamples are generated for each unique sample, preparative and analytical resources will be rapidly expended. Logistical calculations of this type are absolutely essential before a sediment sampling program is initiated.

Given the resource constraints that inevitably accompany sediment sampling, sites must be selected far more judiciously than is the case for water sampling. Even the process of acquisition of samples, whether they are analysed or not, is far more time consuming than for water sampling. The practical consequence is that usually only sites that are suspected to be impacted can be sampled, along with a small number of matched control sites. For lentic wetlands, sampling activities may concentrate on alluvial fans, or other well characterised sites of deposition. For lotic wetlands, the areal distribution should probably first be assessed using total (that is, unfiltered) water samples collected during and immediately after a discharge event.

It should also be remembered that very short range spatial variations may be significant in the case of sediment indicator values, and this is exacerbated by variation in the deposition patterns of plant degradation products.

2.2 Measurement of pore-water indicators

Where sediment contamination by toxicants is suspected to contribute to wetland degradation, it is advisable to determine pore-water concentrations of the relevant indicators. For many toxicants, 'sediment' toxicity is closely related to pore-water concentrations. The most convenient means to examine pore-water is by using 'peepers' which comprise a number of compartments arranged vertically on a rigid support. The compartments are filled with high-purity water and sealed with a dialysis membrane. The peeper is driven into the sediment and over several days the pore-water solution concentrations equilibrate with the water inside the peeper compartments at the various depths.

Other methods of sampling pore-water include displacement from a sediment core with an immiscible solvent such as chloroform, and pressure displacement (squeezing) using an inert gas (such as argon) to drive a piston.

2.3 The vertical dimension

When sampling sediments, it is usually advisable to acquire a core. Surface scrapings are sometimes acceptable, but more so with soils, where the site to be sampled can be directly observed. The risk with surface scrapings in wetlands is that they will be dominated by partly decomposed plant material rather than sediment *per se*. There is little likelihood that such samples would be representative of the indicators of interest.

A sediment core allows an assessment to be made of the vertical distribution of the relevant indicators, that is, how far the species have penetrated into the sediment. In the absence of evidence to the contrary, a core would usually not be sampled deeper than 20 cm. How this is divided depends on the number of subsamples that can be feasibly analysed from each core. If two subsamples are taken, these may be 0–10 cm and 10–20 cm; for three subsamples, 0–5 cm, 5–10 cm and 10–20 cm; and for four subsamples, 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm. Each subsample is then dried and sieved to the required size fraction (usually 2 mm). Sieving is normally sufficient to homogenise the sample.

2.4 Quality control in sediment sampling

Quality control is far more difficult with sediments than with water samples, primarily because of the awkwardness of sample acquisition, transport and storage, and the opportunities that this presents for compromise of the sample. Quality assurance is also more onerous, partly because of the additional resource requirements to analyse QA samples, but also because the acquisition of comparable replicates and reference samples is difficult.

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Management issues for northern Australian wetlands

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Abstract

Wetlands of northern Australia are under increasing threat due to changes in the water regime, pollution, invasive species and physical alteration. Management issues also include the continued development of tourism and recreational facilities, mining and agriculture. Whilst such problems occur the wetlands are relatively intact compared to those elsewhere in Australia. Nevertheless, active conservation management is required and priority actions and sites need attention. An overview of the major issues affecting wetlands in northern Australia is given.

Keywords: wetlands, northern Australia, threats, issues, management priorities

1 Introduction

The ecological character of wetlands in northern Australia (the Wet-Dry tropics) has been described and the major threats or management problems identified (Arthington & Hegerl 1988, Finlayson et al 1988, 1991, Finlayson & von Oertzen 1993, Blackman et al 1993, Fleming 1993, Jaensch & Lane 1993, Jaensch 1994, Finlayson et al 1998, Storrs & Finlayson 1997). These reviews and more recent reports on specific localities (see, for example, papers in Finlayson 1995, Jonauskas 1996) have also identified major gaps in our knowledge of management issues (threats) affecting wetlands.

Comprehensive information on the extent of wetland loss and degradation in northern Australia is not available. Further, most of the information only addresses the 'apparent' reasons for wetland loss and degradation (such as weed invasion, drainage) and little attention has been directed towards the 'underlying' socio-economic and political reasons. General information on the underlying reasons for wetland loss and degradation can be found in Hollis (1992), Finlayson (1994), Hollis & Finlayson (1996), but there is little information specific to northern Australia.

Information on the apparent reasons (*sensu* Hollis 1992) for wetland loss and degradation is uneven. An overview of this information is presented below, based primarily on reviews by Storrs & Finlayson (1997) and Finlayson et al (1998). The overview is based on information obtained from the literature and from workshops held to address management and research issues (see above references). The major management issues are described under the following headings: water regime; water quality; biodiversity and conservation; sectoral and social; and restoration and creation. Given that some issues have multiple effects on wetlands they are mentioned under more than one heading.

2 Water regime

The water regime of wetlands across northern Australia is increasingly being adversely affected by human activities. These include the construction of barrages and dams, and the expansion of irrigation, agriculture and mining. Added to this is the 'wicked' problem of global climate change and sea level rise (Bayliss et al 1998). Thus, the water regimes are being altered – flows disrupted or even stopped, water diverted and stored, and released aseasonally. Effective management of the water regime entails a holistic approach that includes steps to address catchment and even inter-catchment and global influences. The water regime of a wetland should be considered as an all encompassing concept that is comprised of a complex set of processes that affect most aspects of a wetland. These include the source, amount, and spatial and temporal distribution of sediment inputs, and the distribution of the biota.

Further, the water regime is widely recognised as probably the single most important determinant for the establishment and maintenance of specific types of wetland habitats and wetland processes. Gehrke (1995) claims that '*The combined effects of river regulation pose the greatest threat to aquatic ecosystem processes...*'. Fortunately, the massive changes to water regimes, as seen in southern Australia (see, for example, Gehrke 1995) are not as common in northern Australia. Therefore, when referring to water regimes, northern Australian wetlands are comparatively undisturbed. Lake (1995), however, issues a note of caution and warns that the wetlands of northern Australia are being exposed to threats before there is even a rudimentary understanding of their ecology.

Overall, regulation of the water regime for human and agricultural use is not currently a widespread concern. However, the environmental and economic implications of constructing dams/barrages on the highly seasonal rivers and estuaries are not known.

2.1 Irrigation and agriculture

Major alteration to the water regime for human and agricultural use has greatly affected the Ord River in the Kimberley. The Ord is regulated by two dams, one at Lake Kununurra constructed in 1963 and the other at the larger Lake Argyle which was completed in 1972 and located 52 km upstream (Graham & Gueho 1989). It is planned to augment the 15 000 ha of land currently irrigated by a further 25 000 ha and eventually reach 70 000 ha in total. Nevertheless, the success of the Ord River Irrigation Area, after a long period of cropping and marketing trials, could encourage further damming of rivers. Sugar cane has recently been hailed as a successful crop and there are plans to recommence cotton growing (ASTEC 1993). There are also increasingly regular calls for the development of other irrigation schemes (eg on the Fitzroy River in Western Australia).

In the past, broad-scale agriculture in northern Australia has not been overly successful with the failed rice development at Humpty Doo in the Northern Territory being a well known example (Mollah 1982). The problems with agricultural development in northern Australia were critically and controversially identified two–three decades ago by Davidson (1972). Agriculture has been constrained by infertile, leached soils, a harsh climate, and an abundance of pest species. Cropping and horticulture are not major issues within wetlands in northern Australia. However, further development for agricultural use cannot be ruled out. This includes regulated grazing of buffalo and cattle, and the development of land for horticulture, rice and tree crops such as mangoes and cashews.

As a consequence of the construction of the dams on the Ord the river now runs all year round downstream of the dams and discharges into Cambridge Gulf. Thus, the Ord is now one of a small number of perennial rivers in northern Australia. There is little information on the effect of the river flow on the wetland conservation area of Parry Lagoons downstream of the dams (Graham & Gueho 1995). Further, the effect on the groundwater has not been ascertained. The importance of seasonal flows along these rivers for stimulating fish migrations and spawning and to flush vegetation and sediment from channels and waterholes is now well known (Griffin 1995, Lukacs 1995, Bishop et al 1995). Continuous flow or aseasonal releases of water can degrade the river channels through waterlogging of the banks and consequent slumping, loss of riparian vegetation, increased erosion and sedimentation, and encouraging the establishment of weed species (Bunn & Davies 1995, Lukacs 1995).

2.2 Grazing and ponded pasture

The water regime of wetlands is also under threat from steps to increase the potential for grazing of cattle and buffalo. Specifically, the construction of ponded pastures, usually with introduced grass species, has become a contentious issue in Queensland and is developing in the Northern Territory. Large scale artificial ponding on the floodplains has the potential to diminish the primary productivity of the estuaries by retaining water rather than allowing it to run-off at the end of the Wet season (Griffin 1995). In the Northern Territory, such ponding is primarily an issue on the Mary River and it is intertwined with attempts to combat premature drainage of freshwater and intrusion of saline water into formerly freshwater habitat following the breakdown of the natural levees (Griffin 1995). Ponded pastures have not been widely established on Northern Territory wetlands, but they have certainly attracted great interest and could become more favourably viewed by pastoralists. The grass species that have been introduced to such ponds in coastal Queensland have already been introduced to Northern Territory floodplains (Clarkson 1995, Fulton 1995, Jaensch et al 1995).

Humphries et al (1991) stated that perhaps the most insidious and uncontrolled threat to the native communities of northern Australia are introduced pasture grasses, which are implicated in causing changes to ecosystems by changing fire seasonality, intensity and area of burn. Introduced semi-aquatic grasses currently promoted for ponded pasture are infilling tropical wetlands and threatening waterfowl habitat.

The Northern Territory Department of Primary Industry & Fisheries (DPIF) is currently widely promoting the use of some very invasive introduced pasture species at field days and through extension literature, for example olive hymenachne (*Hymenachne amplexicaulis*), aleman grass (*Echinochloa polystachia*) and para grass (*Brachiaria mutica*). These species are included by Humphries et al (1991) in their list of the 18 'top' environmental weeds in Australia. With the DPIF actively promoting these species before research examining the effects of proposed introduction can be undertaken, this effectively means that by the time it is known, one way or the other, it may be too late. There is clearly a need to improve the consultative processes between stakeholders, in order to minimise future possible conflicts.

2.3 Mining

The water regime of wetlands can be altered by mining developments in two main ways – water diversion and storage, and changes in sedimentation patterns. These are both likely to be known quantities and can be controlled. Mining can affect wetlands; in most instances this can be confined to the river or to the catchment downstream (Lake 1995). Mining for minerals in northern Australia does not currently greatly affect the water regime of wetlands. Mining for uranium occurs adjacent to wetlands and streams in Kakadu National Park, but not actually in the wetlands.

Sand extraction from streams is a different story. Extraction of sand from the Mary River has altered sedimentation patterns and offshore shoals in van Diemen Gulf (Sessional Committee on the Environment 1995). The large scale extraction and later discharge of groundwater, as is proposed for the Century mine in north-western Queensland, has introduced a new and controversial management issue. There is also potential for the development of new mines and even dredging operations in wetlands, such as those being discussed for diamond extraction from Cambridge Gulf in Western Australia. Thus, whilst mining is not currently causing great disruption to the water regimes of wetlands in northern Australia, there is considerable potential for this to change rapidly.

2.4 Climate change

Coastal wetlands are generally low in elevation and therefore vulnerable to climate change, including sea level rise. This is a pertinent issue in northern Australia where macro-tidal ranges (5–8 m) already occur and storm surges associated with violent cyclonic depressions are pronounced. The extent of vulnerability will depend on the physical characteristics of the individual wetland and coastal conditions. Environmental responses to climate change are manifested through hydrological, hydrodynamic, geomorphological and ecological processes (Bayliss et al 1998). Current scientific wisdom is that global warming will increase over the next few decades with a high degree of probability (Butterworth 1995). CSIRO (1994) have predicted that by 2030 climate in northern Australia will most probably change by: 1–2°C rise in temperature; up to 20% increase in summer rainfall; increase in rainfall intensity; more extreme events, such as floods, hot days and dry spells; 5–15% increase in potential evaporation; stronger monsoonal westerly winds; and 20±10 cm rise in sea level. These changes are sufficient to greatly alter the ecological character (*sensu* Finlayson 1996) of the coastal wetlands and the values and benefits currently derived from them (Bayliss et al 1998).

The extent of ecological change as a consequence of climate change is not known, but Bayliss et al (1998) have drawn attention to the very real possibility that the highly valued freshwater floodplains may become saltflats, which has already occurred, as a consequence of saline intrusion, in the Mary River (Woodroffe & Mulrennan 1993). The lower Mary River is undergoing rapid change (Woodroffe & Mulrannen 1993, Fulton, 1995) and could provide an analogue of global warming induced change (Bayliss et al 1998). To date, an estimated 17 000 ha of freshwater grassland and *Melaleuca* woodland have been degraded by saline intrusion and a further 5500 ha are immediately threatened. Steps to reduce the extent of saline intrusion have been only partially successful. The ecological consequences of the saline intrusion are blatantly obvious (replacement of the highly diverse and productive grass/woodland habitats with salt flats), but the consequences of large scale engineering solutions are not known and are even questioned as being of practical use (Bayliss et al 1998).

Non-coastal wetlands are less likely to suffer such extreme change (usually meaning detrimental change) as a consequence of global warming. In fact, increased or more intense rainfall may benefit many organisms and even create new wetlands and wetland habitats. Increased temperature and more extreme rainfall events could lead to a call for converting wetlands into water storage lakes. Increased growth of aquatic and riparian vegetation could also lead to increased channel blockages and snags. The extent and effect of such changes are not known, although Lukacs (1995) reports that large stands of emergent plants can cause increased sedimentation and siltation of wetlands.

3 Water quality

Mining, horticulture, pastoralism, population centres, tourism and other land management practices can all potentially impact on water quality by increasing nutrient loads, sediment and turbidity levels, and lead to the introduction of toxic substances. Water pollution can occur as a result of direct discharges to streams or water bodies (eg sewage and effluent discharges) or from diffuse (run-off from agricultural lands) or indirect (eg groundwater salinisation) sources.

3.1 Mineral processing and extraction

Finlayson et al (1988) claimed that the major potential pollution threat to water quality in the Northern Territory was from mineral extraction and processing. It is probably more accurate to say that mining provides the major potential point source of pollution and hence is now generally closely regulated. In the past, the example of Rum Jungle Mine was often quoted due to its problems with overburden heaps and copper leachate piles slowly oxidising and producing acid drainage which polluted the East Finniss River. The water in the open-cut pits also became acidic and contained heavy metals, and the tailings dam was a low-level radioactive hazard. Recently, the Ranger Uranium Mine in the Alligator Rivers Region has been the subject of concern over possible pollution of downstream wetland areas, although water from a restricted release zone on the mine has not been released. Any proposed water release from this zone would be subject to a strict regulatory and monitoring regime (Johnston 1991).

3.2 Tourism and recreation

Diffuse pollution could come from a number of sources that differ greatly in scale and potential impact. Chemical pollution from sunscreens, soaps and insect repellents used by swimmers may become a problem in the small permanent waterholes of popular recreational areas, such as those in Kakadu and Litchfield National Parks. A preliminary investigation of the potential for such problems in Kakadu did not find any signs of pollution, although further tests were recommended (Rippon et al 1994). Fuel spillage from commercial boats and shipping in port areas could threaten mangrove habitats. Similarly, a variety of wetlands could be subject to at least small scale pollution from fuel spillages from boats used for tourism and recreational purposes.

3.3 Agricultural chemicals

The wetlands of northern Australia are generally not as subject to assault from pesticides as those in southern Australia. Expanded horticulture and irrigated cropping could alter this. The expansion of the Ord River irrigation system is of prime concern, especially given past experiences with the use of agricultural chemicals in this region. Only limited information on such chemicals in the waterways and wetlands is available. The secondary effects of such chemicals, for example, causing the decline of zooplankton species that prey upon phytoplankton that would otherwise result in noxious algal blooms, are also poorly understood (Lukacs 1995).

The use of herbicides for weed control on coastal wetlands in the Northern Territory has attracted a large amount of support (Schulz & Barrow 1995), but has not generally been accompanied by ecotoxicological assessments using local species. One exception is the investigation into the effects of spraying the floating weed *Salvinia molesta* in Kakadu National Park with a kerosene surfactant mix (Finlayson et al 1994b). Based on ecotoxicological and chemical testing and modelling of potential nutrient release from decaying plant material no adverse effects were detected. *Mimosa pigra* has received a great deal of attention and large scale herbicide control programs using five different herbicides have been conducted (Schulz & Barrow 1995). These chemicals are applied in desperate attempts to control the further spread of this noxious weed. Given the extent of the program, as witnessed by the following comments from Schulz & Barrow (1995) – '*...the largest application of herbicide ever undertaken in the Northern Territory ... and probably the single largest application of Graslan to a wetland environment in the world*', a risk assessment incorporating ecotoxicological testing with local species could be a useful adjunct to the management processes.

3.4 Eutrophication

Nutrient enrichment of waterbodies by cattle and feral animals is of concern, particularly in the more arid areas. Grazing is a major land use in northern Australia and the presence of cattle within catchments presents considerable potential for deterioration of the water quality (Griffin 1995). Trampling and grazing of the vegetation that holds the sediment in place, and the deposition of dung are the major concerns. Subsequent water quality problems, such as eutrophication, reduction in clarity and algal blooms, can result. Flushing of large quantities of dung into rivers and pools early in the Wet season can add significantly to the nutrient pool and biochemical oxygen demand. Natural systems that are highly stratified (eg billabongs) at the end of the Dry season (Walker & Tyler 1984) may in fact become anoxic with the sudden influx of land-derived nutrients.

The disposal of sewage from urban areas is a well documented threat to coastal habitats in Australia. In northern Australia this is likely to occur around the major settlements and possibly also near sensitive recreational areas.

3.5 Salinisation

Salinity is a major concern in the coastal floodplains of the Northern Territory. Saltwater intrusion from the breakdown of natural levees that separate the freshwater floodplains from the tidal rivers and mangroves is a major threat (Woodroffe & Mulrennan 1993, Jonauskus 1996). It is suspected that feral animals may have contributed to these events, but it is equally argued that they are caused by natural processes that are being exacerbated by human activities, including climate change (Woodroffe & Mulrennan 1993, Bayliss et al 1998). Whatever the cause of the problem, it is evident that the floodplains are under threat and that this threat is extending and engulfing grazing land and valuable wildlife habitat (see papers in Jonauskas 1996). Adjacent floodplains have also been subject to saltwater intrusion, but not to the same extent as the approx 17 000 ha alongside the Mary River. Salinisation of the Mary River floodplains probably represents the most widespread water quality problem in northern Australia.

3.6 Burning practices

Fire is a conspicuous element of the northern landscape. The regularity of fire in the Wet-Dry tropics has affected wetlands, but quantifiable information is, on the whole, absent (Douglas et al 1995). Fire remains a contentious issue in the northern landscape (Andersen 1996).

Broadscale fire regimes can affect the water quality of wetlands. Direct effects can result from burning of the dry floodplains and either the loss of nutrients and organic material, or the deposition of excessive amounts of material in waterholes (Roberts 1996). Catchment burning can also effect wetlands by adding ash and suspended solids. Destruction of the riparian zone by fire (and other means) can increase light availability and alter the energy input via leaf litter. The effect of burning practices on aquatic/wetland systems is still poorly known despite the major role fire has in management regimes for the savanna landscape of northern Australia (Douglas et al 1995). Lake (1995) points out that unlike possible pollution from point sources, such as mining developments, other major land use disturbances, such as those resulting from fire and grazing practices, are not strictly regulated.

4 Biodiversity and conservation

The conservation status of wetlands of northern Australia has not been assessed and indicators of ecological integrity have not been developed. It is well recognised, however, that many of the wetlands are valuable for conserving biological diversity, but are under at least 'low-level' threat by increased land use activities and invasive species (Finlayson et al 1988, 1991, Finlayson & von Oertzen 1993). Compared to elsewhere in Australia the wetlands of northern Australia are largely intact. Relatively few have been lost, although mangroves around Darwin are now potentially threatened by infilling and clearing for port and urban developments. The extent of degradation is unknown, although Finlayson et al (1988) and Finlayson & von Oertzen (1993) point out that cattle grazing has degraded the natural vegetation of many wetlands.

4.1 Mangrove degradation

Current threats to mangrove communities are restricted to localised areas in the vicinity of Darwin. Threats arise from nutrient enrichment, construction of causeway embankments, removal and reclamation for new subdivisions, stormwater run-off and changes to the hydrology and salinity gradients from mosquito eradication drains (Dames & Moore 1984). Further pressure is likely to come from proposed recreational, residential and industrial developments around the harbour.

Recognising the need to conserve mangrove and coastal environments, the Northern Territory government has developed a management policy aimed at 'achieving a coordinated and effective approach to coastal management issues' (Singer & Wright 1985). A mangrove resource data base has been established (Dames & Moore 1984) to compile available information on the mangroves of the Northern Territory and associated coastal environments. The data base presently contains an adequate description of mangrove distribution, but little information is available on associated flora and fauna and mangrove dependent marine organisms. Similarly, there is a paucity of information on the response of mangrove communities to disturbance other than a few references to cyclone damage and the effect of sewage effluent.

By international standards the threats from development to Northern Territory mangrove communities are negligible (Singer & Wright 1985). However, without additional carefully-collected scientific data it will be difficult to rationally resolve the conflicts that could arise between conservationists and coastal developers.

4.2 Pest species

The ecological character of many wetlands in Australia has been adversely affected by invasive plants and animals, many of them alien species. Fourteen of the top eighteen environmental weeds in Australia invade wetlands (Humphries et al 1991). Humphries et al (1991) make the points that tropical wetlands and riparian zones are at great risk from weed invasion.

> *'....riparian systems are most heavily invaded within any given environment and are therefore at greatest risk. The importance of these systems, particularly at times of drought, increases the ecological seriousness of this situation.'.*
>
> *'Tropical wetlands are in critical danger.'*

The reasons for weed invasion are manifold, but it is believed that, in the Northern Territory, it is the high levels of disturbance caused by domestic and feral animals to riparian fringes, floodplains and ephemeral flats, that make these areas highly susceptible to weed invasion (Cowie & Werner 1993, Griffin et al 1989, Reid & Fleming 1992). Feral grazing animals have invaded many northern Australian wetlands. Other significant threats come from cane toads (*Bufo marinus*) and exotic fish, particularly the mosquito fish (*Gambusia holbrooki*).

For many of the main pest species the extent of their invasion of wetlands and streams has been described to some extent. In many instances the biology of the species may also be known or is being studied (eg *Mimosa pigra*, *Salvinia molesta*). Surprisingly, however, vital information on the ecological changes wrought by these species is often confined to a few isolated studies, if any, and/or anecdotal evidence. For example, a great deal of effort has been directed towards developing both chemical and biological control of *Mimosa* and *Salvinia*, but relatively little effort has been directed towards assessing the extent of ecological change caused by these species.

Economic analyses of the losses caused by pest species are also not common. These can be done on the basis of lost agricultural production and in some cases (eg grazing land covered by weed species) losses in productive capacity may be very obvious, but economic evaluation of 'natural' wetland ecosystem functions is only in its infancy (eg Turner & Jones 1991). Unless we can 'price' the ecological consequences along with the economic consequences of such massive weed invasion we may never really know the extent of our 'loss'.

In the following text a general description of major pest species is given. A complete list of potential or minor pest species is not given.

4.2.1 *Acacia nilotica* (prickly acacia)

Prickly acacia is native to Africa and West Asia where it is found in acacia-savanna along drainage lines, bores and dams. It currently covers about 7 M ha in arid to subtropical regions of Queensland (Smith 1995). In the Northern Territory, small infestations occur along the Barkly Highway with an outbreak reported on Cattle Creek Station in the Ord-Victoria Plains biogeographical region. Currently, all infestations are under control.

4.2.2 *Brachiaria mutica* (para grass), *Echinochloa polystachya* (aleman grass) and *Hymenachne ampexicaulis* (olive hymenachne)

Para grass, aleman grass and olive hymenachne are grass species that are commonly referred to as ponded pasture species (Clarkson 1995). Para grass is a highly invasive alien species that has spread across many wetlands in northern Australia. In places it has been aided by deliberate plantings as a pasture species and in others it has spread from pastoral areas into nature conservation zones (Lindner 1995, Miller & Wilson 1995, Clarkson 1995). Deliberate planting of para grass now occurs in both Queensland to develop ponded pastures (Clarkson 1995) and in the Northern Territory for stabilising floodplain surfaces following control of mimosa (Miller & Wilson 1995, Cook & Setterfield 1995). Aleman grass and olive hymenachne have been introduced more recently for use in ponded pastures in Queensland (Clarkson 1995) and at a few locations in the Northern Territory.

While there is no rigorous scientific data about the impact of these species, there is a lot of anecdotal evidence that they form a monoculture and are, in certain situations, invasive. This means, at the very least, reduced biological diversity in the affected areas, and therefore structural and functional deterioration of the ecosystem. At worst, it could mean the complete alteration/modification of entire ecosystems. These pasture species are a particularly difficult and even intractable problem given that pastoralists are clamouring for them and conservation authorities are concerned over their potential to completely alter the ecological character of wetlands. Fisheries authorities are also concerned that ponded pastures will prevent freshwater run-off to the estuaries and reduce the primary productivity of these habitats and also prevent migration by juvenile barramundi (Clarkson 1995, Griffin 1995). There seems to have been little attempt to supplant the introduced grasses with native species; presumably due to the ease of establishing the introduced species and their greater value as stock food.

4.2.3 *Eichhornia crassipes* (water hyacinth)

This floating introduced species has long been a major weed in Australia (see Mitchell 1978, Finlayson & Mitchell 1982, Forno & Wright 1981, Wright & Purcell 1995). Biological and chemical control methods have been implemented and it is not now generally regarded as a serious threat to wetlands, although local problems still occur or could occur (Fulton 1995). It is not known if this change has occurred as a consequence of control measures or whether the plant has established a balance after an initial period of explosive growth. It occupies similar habitats as *Salvinia molesta* and presumably has a similar, but largely unknown effect on wetlands.

It is more widespread in coastal wetlands in Queensland (Finlayson & Gillies 1982) than inland. A number of incursions have occurred in the Northern Territory, but is only known to have established at one site, Fogg Dam near Darwin.

4.2.4 *Mimosa pigra* (mimosa)

Mimosa is an aggressive prickly shrub, native to Central America, that can form dense monospecific stands on the floodplains of the Northern Territory. At present, it is confined to the coastal floodplains of the Northern Territory, in an arc extending from the Moyle River in the west to the Arafura Swamps in Arnhem Land (Lonsdale et al 1995). It covers an estimated 80 000 ha and is a prolific producer of seeds that are readily dispersed by water, vehicles and animal vectors. There is strong circumstantial evidence to link vehicle movements with new occurrences (Cook et al 1996). Natural expansion of established stands is very fast.

Research efforts have centred on finding suitable biological control agents with a number having been released. Integrated control programs are also in place and incorporate biological control along with the use of herbicides, mechanical removal (chaining), burning and revegetation (Miller & Wilson 1995, Schulz & Barrow 1995). In Kakadu National Park a continuous 'search and destroy' policy has successfully been in place for the last decade (Cook et al 1996). Outside the park, however, the story is more one of gloom and expensive chemical control programs that are partly government-funded and undertaken on pastoral leases and Aboriginal lands (Schulz & Barrow 1995). Management emphasis on control techniques, particularly biological means, continues and importantly, is now complemented by post-control rehabilitation of the formerly infested areas.

4.2.5 *Parkinsonia aculeata* (parkinsonia)

Parkinsonia is a branched spreading tree from South America. It can grow to 6 m height and in a variety of soil types and is often found around bores, dams and along creeks and riverbanks (Smith 1995). It is widespread on pastoral leases on the Barky Tablelands and in the Victoria River District. Control is undertaken by using biological control agents along waterways and herbicides away from the major waterways. Further, it can dominate the vegetation near watercourses and ephemeral lakes in the Northern Territory, such as the Playford River which terminates in Lake DeBurgh and Corella Creek terminating at Corella Lake (D. Gracie pers comm). Chemical control has been carried out, but discontinued in some areas of the Northern Territory because of the extent of the seed reserves present upstream (D. Gracie pers comm).

4.2.6 *Pistia stratiotes* (water lettuce)

Water lettuce is a floating aquatic plant that was first recorded in the Northern Territory from lagoons near Darwin about 50 years ago. It has since been recorded from a number of locations but does not appear to have caused the serious problems reported elsewhere in

Australia (Mitchell 1978) and there is some question as to whether or not the species is alien or native to the Wet-Dry tropics (Gillett et al 1988). It is important to note though, that under suitable conditions, for example in streams and channels in the lower Burdekin in Queensland (Finlayson & Mitchell 1981) it can become a weed.

4.2.7 *Prosopsis limensis* (mesquite)

A small tree to 6m, mesquite is found on heavier clay and loam soils. It is a native of North and South America and is established as a weed in Queensland and the Northern Territory (Smith 1995). It is found mainly in the Barkly Tablelands with isolated occurrences near Katherine and further south in the arid zone. Mesquite appears to be on the increase on the cracking clay soils of the Barkly Tablelands. Herbicides have been largely ineffective. It is spread readily by stock by ingestion and later defecation, with isolated plants appearing in previously weed free locations (D. Gracie pers comm). A related species *Prosopsis glandulosa* (honey mesquite) has been found on Nicholson Station in Western Australia abutting the Northern Territory border.

4.2.8 *Salvinia molesta* (salvinia)

This free-floating aquatic fern, originally from South America, has been the centre of much attention in Australia and elsewhere (see Mitchell 1978, Finlayson & Mitchell 1982, Harley & Mitchell 1981, Room & Julien 1995, Storrs & Julien 1996). In the Northern Territory infestations have been found at Nhulunbuy, and on the Finniss, Howard, Daly, South Alligator and East Alligator Rivers; the last two in Kakadu National Park (Miller & Wilson 1989, Finlayson et al 1994a, Julien & Storrs 1993). It is not widespread in the northern region of Queensland, but major outbreaks have been recorded in regions outside of the Wet-Dry tropics, such as near Mt Isa (Finlayson et al 1984 a, b) and along the east coast (Finlayson & Gillies 1982, Harley & Mitchell 1981, Finlayson & Mitchell 1982).

Several infestation have been successfully eradicated by the DPIF using herbicides, including a major infestation on the Adelaide River in the Northern Territory (Miller & Pickering 1988). Generally, management is reliant on biological control using an introduced weevil that has had variable levels of success (Room et al 1981). Storrs & Julien (1996) have recommended the adoption of integrated control measures with chemical spraying being strategically allied with attempts to spread the weevil to all known infestations. The use of herbicides in some locations raises many concerns; some of these were addressed by Finlayson et al (1994a).

Despite being a widespread weed in eastern Australia for more than three decades very little is known about its ecological effect on wetlands. Salvinia competes directly with other plants for light, nutrients and space. The weed invariably becomes dominant over submerged floating plants and smaller floating plants, such as *Azolla* and *Lemna* spp., by cutting off their light supply. The water under a salvinia mat has lower oxygen and higher hydrogen sulphide concentrations, lower pH, and higher temperature than open water nearby (Mitchell 1978). It also dramatically alters the nutrient status of billabongs (Storrs & Julien 1996), reducing nutrient availability to other biota, through growth or storage within the plant (Finlayson et al 1984 a, Room 1986).

4.2.9 *Bubalis bubalis* (Asian water buffalo)

The feral Asian water buffalo once proliferated on the coastal floodplains of the Northern Territory and were considered responsible for widescale destruction of the native vegetation by direct grazing, trampling and wallowing and indirectly by destroying levee banks and contributing to premature drainage of freshwaters (see Finlayson et al 1988). However, throughout the 1980s the feral herds to the west of Arnhem Land were almost eradicated as part of a national program to prevent diseases being transferred to domestic stock. Buffalo still exist in large numbers in Arnhem Land as this area was not involved in the eradication program.

The problem, perhaps ironically, is now not so much one of too many buffalo, but one of too few buffalo! The rapid removal of a major grazer from the floodplains and billabongs has resulted in large scale ecological change (Finlayson et al 1991, 1993). Both native and alien plant species have spread to cover the areas formerly laid bare by the buffalo; billabongs have become choked with red lilies and sedges, and grasses, including para grass have overgrown stream and billabong banks and spread across the floodplains. In this instance the ecological consequences of removing the buffalo and thereby overcoming one series of problems, did not seem to receive sufficient attention.

It is important to note, however, that the impetus for removing buffalo came from funding provided for disease control in feral stock; environmental concerns were not to the forefront (Skeat et al 1996). Given that funding was not given for large scale environmental management it is expected that buffalo numbers will naturally increase again in areas such as Kakadu after the disease eradication program funding ceases in 1997.

4.2.10 *Sus scrofa* (pig)

The feral pig is widespread over the Australian environment. It has caused widespread damage around the edges of wetlands and adjacent forests. This disturbance provides great potential for the rapid establishment of weed species. The implications for the lack of control of pigs on weed management are very serious. In the Northern Territory there is evidence that pigs have proliferated following the removal of the feral buffaloes from the floodplains (Corbett 1995). This seems reasonable given that many buffalo were shot from helicopters and their carcasses left on the floodplains and that buffalo formerly trampled and destroyed many vegetative morsels that would have been favoured by the omnivorous pigs. However, the influence of climatic factors, for example, on pig numbers can not be discounted as a contributory factor.

Control of pigs is widely regarded as difficult depending on the terrain. Control programs utilise trapping, hunting with dogs, poisoning and helicopter shooting. A further factor to consider when assessing the effect of pigs on the environment and the need for control measures is the increasing acceptance of pigs by some Aboriginal people as part of their life style.

4.2.11 *Bufo marinus* (cane toad)

The cane toads have been present along the eastern coast of Queensland since the 1930s and over the last decade have moved westwards into the Northern Territory to the vicinity of the Roper River. The rate of natural spread of the cane toad is approximately 30 km per year (Freeland & Martin 1985). The available data do not support the notion of the cane toad having a long term catastrophic impact on native fauna. No species in Queensland has become threatened or gone extinct as a result of the cane toad's introduction 50 years ago (W. Freeland pers comm). Recent studies on the toad indicate that whilst all stages of the life cycle are potentially toxic and are avoided by many predators they are successfully consumed by others (Alford et al 1995). Some native frog larvae and snails are negatively affected and toad larvae can compete strongly with larval native frogs. There is strong anecdotal evidence that predators such as goannas initially decline after the arrival of cane toads, but after a short period re-establish and/or learn more effective techniques of consuming the toads and avoiding the toxins that they carry (W. Freeland pers comm).

The reaction of local Aboriginals to the impact of toads on their traditional food sources is not known (P. Whitehead pers comm). Noting that Aboriginal people are increasingly accepting feral animals as part of their 'traditional' lifestyle it could be pertinent to incorporate an Aboriginal perspective on this species before further effort is expended.

4.2.12 Exotic Fish

No major exotic fish incursions have yet happened in northern Australia. This contrasts markedly with the dominance of introduced species, especially trout, carp and mosquito fish, elsewhere in Australia (Arthington 1986, Fletcher 1986). Localised incursions of several freshwater aquarium species have occurred in the Northern Territory. Guppies (*Poecilia reticulata)* are established in Nhulunbuy Town Lagoon; platys, mollies and swordtails (*Xiphophorous maculatus*, *Poecilia latipinna*, *Xiphophorous helleri)* in Gunn Point Creek (believed to be escapees from the Prison Farm!).

Mosquito fish (*Gambusia holbrooki*) have been actively introduced into much of southern and eastern Australia as a means of controlling mosquitoes. They occur in northern Australia at localised sites. They are voracious feeders and seemingly have a major influence on the structure of invertebrate communities without being very successful in controlling mosquitoes. For any eradication strategy to be accepted the ecological degradation caused by these fish needs to be demonstrated; this information is either inconclusive or is lacking (Fletcher 1986).

4.3 Riparian degradation and grazing

Soil erosion due largely to land management practices has been a feature of the riparian areas of many large river systems of northern Australia (eg Ord and Victoria) causing siltation and filling of waterholes, collapse of bank structure and loss of riparian vegetation (Winter 1990). Land degradation and habitat alteration caused by the introduction of exotic herbivores appear to be the principal factors causing change in status of birds in arid Australia. Introduced predators are implicated in some cases and altered fire regimes may play a part (Reid & Fleming 1992).

Overgrazing by cattle and feral animals can lead to pronounced seasonal and other changes in run-off patterns and to increased sediment loads. Vegetation changes, chiefly involving the replacement of deep-rooted trees by shallow-rooted grasses, can also lead to marked changes in hydrological patterns as well as changes in water quality, of which increased salinity can be among the most important.

The spatial extent and intensity of the domestic stock threat varies from region to region dependent on the distribution of commercial livestock grazing and individual property management approaches (J. Reid pers comm). Riparian zones (fringing vegetation), particularly around permanent waterholes which are the foci for water-dependent (drinking) grazing animals, have probably been most degraded in terms of vegetation compositional and cover changes. Increasing damage occurs as conditions become drier (drought) and as animals become more focused on remaining watering points (J. Reid pers comm).

5 Social and sectoral issues

The utilisation of wetlands and wetland products raises a number of specific and general concerns for conservation and land/water management agencies. Access to and maintenance of the ecological character of the wetland habitats have received a great deal of attention and been subject to land use planning and zoning. However, often this has been done on a sectoral basis with little regard for other sectors or groups within society. The advent of widespread tourism and recreational activities has seen conflicts develop over access for recreational fishing (Julius 1996). Further, quarantine measures for weed control have been controversial, such as those on the Magela in Kakadu for salvinia and for noogoora burr on the Ord River.

In many instances the management agencies and policies required for effective wetland management, especially multiple use, have been inadequate. Attempts to break down such sectoral divides have seen the Northern Territory Government conduct extensive consultation and form committees to address the complex problems on the Mary River wetlands. Further, there are ongoing concerns about management of and access to Aboriginal-owned wetlands.

In the following discussion major social uses of wetlands are addressed in terms of their effect on biological diversity and conservation. Thus, some of the issues that are addressed under headings above are reintroduced but with a different emphasis. It is perhaps instructive to note at this stage that sectoral divides and associated underlying socio-economic and political issues that affect land use decisions are being seen more and more as the prime reasons for ineffective wetland management (Hollis 1992, Finlayson 1994, Hollis & Finlayson 1996).

5.1 Tourism and recreational activities

Recreation activities in wetland areas include picnicking, camping, boating, hunting, bird watching, bushwalking and amateur angling. Tourism and recreational activities are strongly influenced by factors such as the presence of water and accessibility. Access to many wetlands is limited for much of the year to specialised vehicles. As a result, wetland recreational use is generally restricted to floodplain edges, billabongs and major channels or creeks. Vehicular access has caused erosion along levee banks resulting in denudation of billabong and river frontages. Similarly, poorly chosen or constructed boat launching facilities can cause erosion. These problems can be overcome by excluding vehicles from the forward slopes and adopting some care when choosing and constructing boat ramps. More difficult problems to overcome include the dispersal of seeds of noxious weeds, disruption of breeding colonies of waterbirds (Jaensch et al 1995) and pollution of waterholes (Rippon et al 1994, Lindner 1995) by vehicles and boats.

Hunting is a particularly controversial recreational issue with great concern being expressed over the ethics of such activities. Hunting disturbs breeding birds (Jaensch et al 1995) and can result in lead poisoning of birds from spent shotgun pellets (Whitehead & Tschirner 1991). Hunting of geese by non-Aborigines has recently undergone increased regulation and has been subjected to intensive research and monitoring, especially in the Northern Territory. Aerial surveys are used to acquire data for determining the timing and duration of the hunting season and bag limits. Current hunting pressure does not appear to be heavy in relation to the size of the waterfowl populations. In view of an expected increase in hunting activities the recent steps of initiating research and maintaining contact with the hunting fraternity are timely. Hunting by Aboriginal people also occurs, but this is generally unregulated and at times controversial (see Ponte et al 1994).

Probably the most important recreational activity in northern Australian wetlands is fishing, especially for barramundi (*Lates calcarifer*). The environmental impacts of large numbers of anglers extend beyond placing pressure on fish stocks; however, there is very little information on the extent of this pressure. Barramundi stocks in the Northern Territory were over-exploited during the late 1970s and early 1980s leading to extensive regulation of both commercial and recreational fishing (Grey & Griffin 1979, Griffin 1995). Recreational fishing is particularly important on the Mary River and in Kakadu National Park in the Northern Territory (Griffin 1995). Given the popularity of recreational fishing there is an increasing problem of 'overcrowding' at highly favoured or easily accessed sites.

The current low level of recreational impact on northern Australian wetlands is probably attributable to low population pressures. With increased population growth (currently 3.8% per annum) and tourism (increasing at 15% per annum), however, the pressure is due to increase (Taylor et al 1985). Without sound management practices environmental degradation could cause a reduction in the current aesthetic and recreational value of these areas.

5.2 Pastoralism

Pastoralism has been the most extensive land use in northern Australia since European settlement and is currently the major land use outside of nature reserves (Whitehead et al 1992). The wetland areas are the most nutrient rich and mesic areas and thereby produce the best forage for livestock. There is much debate on the efficacy of pastoral activities in northern Australia with a popular conception being that conservation objectives can only be met by the complete removal of grazing. Pastoralists counter that they are modifying their management practices (Curry & Hacker 1990, Cadzow 1993) and point to Landcare initiatives as evidence. However, there are differing views of the usefulness of Landcare in the rangelands context and critics claim that Landcare has been appropriated in some instances by entrenched interests thereby excluding innovation (Reid 1994).

Widespread modification of floodplains to achieve pastoral objectives will probably reduce the range of wetland habitats (Whitehead et al 1992). There is increasing pressure on wetlands as alternative sites for grazing during the Dry season. Further, exotic pasture species such as para grass (*Brachiaria mutica*) are being introduced into areas formerly occupied by native grasses (Liddle & Sterling 1992) to increase productivity. It is feared that homogeneous and 'regulated' floodplains will not show the idiosyncratic response to variable rainfall that maintains the current habitat diversity (Whitehead et al 1992). The actual role of grazing in maintaining habitat diversity is not clear and under some circumstances it could be used to promote vegetation diversity. However, the introduction of exotic grass species that displace native species (Cowie & Werner 1993), especially if coupled with ponded pastures (see above) is not generally supported by conservation and fisheries interests (Whitehead et al 1992; Griffin 1995, Jaensch 1995) and is, at times, a highly emotive issue (Julius 1996).

5.3 Aboriginal land usage

Under the Northern Territory Land Rights legislation Aboriginal people have regained large areas of traditional land – most often in drier areas, wetlands and other places not wanted by non-Aboriginal people. Nearly a half of the Northern Territory is either Aboriginal land or under claim and over 85% of the coastline is now owned by Aboriginal people. Economic activity on Aboriginal land contributes significantly to the northern Australian economy. All the major mines and on-shore oil and gas wells in the Northern Territory are on Aboriginal land as well as some large scale cattle projects. The main tourist destinations including Kakadu and Nitmiluk (Katherine) National Parks are on Aboriginal land and Mabo-style land claims have been placed on other parks and vacant crown land.

Effective management of wetlands on Aboriginal land may require implementation of more appropriate locally driven agreements, covenants and protocols that reflect specific cultural heritage values. For this to be achieved consultation mechanisms may need to be reassessed and the political problems of land rights resolved (Graham & Gueho 1995). Assistance with best-practice environmental planning should be linked to full acceptance of the values and knowledge of Aboriginal peoples (Christopherson 1995). The issue of local community empowerment in conservation and land management is still vexed, but given the conservation value of wetlands on Aboriginal land across northern Australia it should not be ignored.

5.4 Burning practices

As already mentioned, fire is an integral and controversial aspect of land use and management in northern Australia. However, there is little actual research on the effect of burning patterns on wetland organisms and habitats. Douglas et al (1995) have reported on experimental work in streams. Traditional Aboriginal knowledge on fire behaviour still exists and Roberts (1996) reports that it has been used as the basis for directed and highly controlled resource management. Thus, it has been used to clear land for hunting purposes or to replace unwanted grasses, to break up the country into mosaic patterns and avoid destructive peat fires on the floodplains. Much of this knowledge has not been documented (Roberts 1996).

Land uses greatly affect the fire regime on wetlands and in conservation reserves there are attempts to prevent late Dry season burns (Press 1988, Graham & Gueho 1995). However, unregulated human activity can make this a difficult task with inappropriate fires being common. Grazing may impart some form of control over fire on floodplains by reducing the fuel load, although this is being affected by the introduction of exotic grass species and the removal of buffalo. Overall, the effect of fire on wetlands is little understood despite being a regular feature.

6 Restoration and creation

Given the large extent of wetlands in northern Australia and the comparatively low level of degradation and loss, compared to southern Australia, very little attention has been directed towards restoration and creation. The examples of Rum Jungle and the Mary River are two major exceptions (and are described above). The Rum Jungle restoration process was one dominated by removing or reducing the source of contamination from the abandoned mine site. The Mary River situation is far more complex with competing land uses and a seemingly intractable process being driven by geomorphic forces.

Small lakes, such as that in Jabiru in the Northern Territory have been constructed but these are not common. The lake created at Fogg Dam in preparation for the rice growing ventures of the 1960s is now a valued conservation reserve and has been greatly modified to attract specific types of waterbirds. Such schemes have great public appeal and education value.

Far more attention is being directed towards the use of wetlands for treating wastewater, particularly that from mine sites (Noller 1995, Noller et al 1994, Nisbet 1995). This technology has been developed and trialed in southern Australia for urban and agricultural wastes (see, for example, Finlayson et al 1986, Finlayson & Mitchell 1983); however, it has only recently been adopted in northern Australia for mining wastes. Wetland plants are known accumulators of heavy metals (Finlayson et al 1984b, Outridge & Noller 1991) and can filter and retain suspended sediments (Finlayson & Chick 1983). Noller (1995) identifies three classes of wetlands as suitable for potential amelioration of mine wastewaters: existing wetlands; enhanced existing wetlands; and artificial wetlands. Both natural and artificial wetlands are being tested at the Ranger uranium mine in the Northern Territory for potential use during the operational phase of the mine and for long term passive treatment after rehabilitation of the mine site (Nisbet 1995).

Baird et al (1995) point out that whilst the capacity of wetlands to act as sinks for waste products may provide a powerful argument for their conservation it is also a dangerous one, since they effectively become surrogate landfill sites. Further, they argue that '*While it is true that wetlands obviously have a tremendous capacity to accumulate and store chemical wastes, including contaminants, the concept of assimilative capacity of such systems is rarely addressed, except perhaps in terms of their capacity to store nutrients and some trace* *metals* ...'. Overall, despite a lot of attention, there is a lack of information regarding the sustainability of wetlands when they receive significant inputs of contaminants. Thus, there is obvious concern over the use of natural wetlands for these purposes. The use of artificial wetlands may bypass such concerns, but not if they are also used as an excuse to degrade nearby natural wetlands. Similarly, enhancing degraded natural wetlands for wastewater treatment could be a double edged sword. Baird et al (1995) query whether wetland filters have a place in serious conservation strategies for wetlands.

7 Management priorities

The geographical area covered in this review is both large and sparsely populated. Nevertheless, many wetlands have been disturbed, or are threatened with disturbance. These disturbances could cause a reduction in, or total elimination of, one or more of the major biotic components, or a reduction in the diversity of wetland types. Whatever the type of disturbance, management for sustainable development (ie including conservation) should be designed to minimise unacceptable impact on the basic ecological character of the wetland. Determining what is an unacceptable impact is obviously a difficult task and must involve the myriad of societal considerations that are associated with land use planning. This task will be reliant on an adequate inventory of wetland values and benefits backed by rigorous risk assessments, monitoring and, where necessary, restoration of degraded habitats.

With the need for a valid and comprehensive information base in mind the following recommendations for regional priorities are presented.

7.1 Reserve system

Extension of a representative system of nature reserves and parks is one way of initiating processes that are required to enable wetland species and habitats to be conserved. By itself, however, the proclamation of reserves may not achieve a great deal. It is also necessary to develop and implement management practices that recognise the linkage between adjacent land uses and conservation management, especially where more than one jurisdiction is involved. It is essential that the reserve system is based on a sound inventory and is representative of local conservation needs and takes into account the historical land uses and future expectations of the local community. This may sound extremely complex, but it does provide the basis for local involvement in conservation associated with multiple land use planning at both a site and catchment level. In some instances, new or revised legislation and policies may be needed to underpin multiple and sustainable land use practices that provide the basis for successful conservation. Planning to incorporate tourism and recreational activities and access by traditional Aboriginal occupants and/or owners may also be needed at this stage. The use and regulation of fire for specific purposes may require specific attention.

7.2 Weeds

Weeds, particularly, *Mimosa pigra,* pose a major threat to wetlands of northern Australia. The potential of weeds such as *Mimosa pigra* and *Salvinia molesta* to cause problems is well established and it is generally accepted that they should be controlled, if not eradicated. The status of other species is not always so clear and should be assessed on both a local and a regional basis. Such assessments should be done on a thorough analysis of known risks and hazards and include an analysis of the secondary consequences of the preferred control techniques. Unless the problem of weed invasion is addressed on the basis of sound and even proactive risk assessments the basic character and value of the wetland habitats could be degraded or even lost. Control techniques must be monitored as must the target areas after the control has been effected and, if necessary, further rehabilitation steps taken to stop reinfestation by the same or even other weed species.

7.3 Feral animals

Feral animals are present in many wetlands and, in some instances, have caused considerable disturbance to the natural system. The most prominent example, the Asian water buffalo on the coastal floodplains of the Northern Territory, has been subject to large scale control as a consequence of concerns over the spread of diseases to domestic stock. Once this program ceases the possible reintroduction of buffalo, whether through natural population growth or deliberate actions, should be handled with care. As with any management strategy, the success and effects of both the control program and any reintroduction need to be monitored and, if required, adjustments made. The impact and control of other feral animals needs to be assessed to provide the basis for conservation strategies to be implemented to prevent or reduce further undesirable change.

7.4 Agriculture

Agricultural development often results in diffuse sources of pollution and can have a significant effect on wetlands. Whilst it is difficult to control diffuse source pollution, attempts should be made to limit the extent of run-off of nutrients and pesticides from agricultural land to wetlands. To be fully effective this should involve management of the entire catchment and even the application of rigid controls such as those used to regulate mining enterprises. If the nature of the problem is assessed prior to development and adequate controls devised, the need for future remedial actions could be avoided. Point sources of pollution can be readily identified and are often, at least locally, extremely detrimental to the integrity of wetlands. Grazing is a particularly complex problem in some wetlands, especially if linked with the introduction of exotic pasture species and ponded pastures. Further attention, perhaps preceded by a moratorium on further introductions and ponding of floodplains, to the consequences of these actions is needed.

7.5 Tourism and recreational activities

The continued expansion of recreational activities into wetlands is likely to be a major problem for conservation authorities. The main areas of concern seem to revolve around the development of infrastructure and the extent of fishing activities. Tourism is a rapidly expanding industry and often linked with water and wetlands. Management plans that consider the potential impact of and even competition between recreational activities as diverse as fishing and hunting and bird watching are required.

7.6 Climate change

The problem of global climate change is probably one of the most perplexing for wetland managers. In the Northern Territory there is a suggestion that the salinisation of large areas of coastal floodplains may be due to natural processes. Thus, attempts to rectify the loss of freshwater habitat and prevent further extension of this loss may be attempting to combat natural processes. Monitoring of coastal processes and the rates of change are required as a base for planning further management steps even as current intervention steps are implemented. Management planning for such large problems will inevitably reflect community values and technological feasibility, but should not go ahead in ignorance of natural variability and environmental change. The problem of saline intrusion is seen as one of the most challenging for land owners and environmental planners alike, especially if linked to global scale climate induced changes.

7.7 Clearing and waste disposal

Clearing of wetlands for urban and industrial facilities is not widespread, but does have local impact. The retention of natural wetland functions should be at the fore of plans to develop such wetland habitats. On the same token the potential of artificial wetlands constructed to treat wastewaters should not be used as an excuse to degrade existing wetlands; it is not possible to fully replace the functions and values of natural wetlands with artificial wetlands. Further, the disposal of wastewater via natural wetlands should be discouraged unless it can be shown that the wetlands are not significantly altered. In this instance, further research into basic wetland processes and functions is needed.

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Mine water and waste management

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Abstract

Mines are important in wetland management because they usually degrade the water that they use, and because of their often remote location may be the major source of contaminant input to wetlands nearby. Mines use water for a number of purposes, with the degree of quality impairment dependent on the use and the extent to which the mine is required to ameliorate the degradation. Mines acquire water from a number of sources, and withdrawal of supplies from wetlands, if this occurs, may be as detrimental to the wetland environmental values as the addition of contaminants. Mines tend to categorise and store water according to the concentration and nature of contaminants contained in it. This is because the management of degraded water depends on its quality, and whether waste water can be released to the environment, either before or after treatment. These aspects of water use and management within mines are illustrated with reference to the Ranger Uranium Mine in the Northern Territory.

Keywords: mining, water use, waste water management, Ranger Uranium Mine

1 Introduction

Mines are significant users of water, and except in the case of elaborate water treatment, degrade the quality of the water, as determined by the presence of elevated concentrations of 'chemical indicators'. The exact nature of the chemical species added to water by the mining and milling process depends on the nature of the mine, and the degree of beneficiation of the ore on site. However, most mines will contribute to substantial increases in the turbidity and salinity of much of the water that they use, and most probably the mineral that the mine exists to exploit. Often mining activities will result in the release of significant quantities of acid (ie reduction in pH), and this will especially be the case where the ore or waste rock contains sulfide mineralisation that will oxidise to sulfuric acid on exposure to air.

It is self evident that increased burdens of mining-related materials in surface and groundwater can place additional stresses on wetland ecosystems, and the management of wetlands downstream from the mine depends critically on suitable monitoring and control of mining-related pollution sources. Because mines are frequently located in remote areas, they (and the urban infrastructure built to service them) may constitute the overwhelming source of anthropogenic physico-chemical inputs to wetlands in otherwise relatively undisturbed regions.

2 Uses of water in mines

2.1 Dust suppression

Blasting and excavating activities, and the deployment of heavy equipment, particularly trucks, over ore stockpiles and waste-rock dumps raises nuisance dust. In the case of uranium mines the dust must be suppressed to prevent exposure of workers to unacceptable levels of radiation. In general, water used for this purpose is of intermediate quality (non potable).

2.2 Mineral separation from waste material

At most mines, the raw ore is processed to some extent on site. Ore is usually crushed, then ground to a fine texture (commonly in the 1 μm range). The ground ore may then be mixed with water and a flotation reagent added. This facilitates the entrainment of the mineral grains in a froth, which floats to the surface and may be skimmed. While most of the organic frothing agent is broken down during further beneficiation of the ore concentrate, some remains in the water used for the process, and must be properly stored and disposed of. The waste ore fraction would normally be consigned to tailings after removal of water through settling or centrifugation.

2.3 Leaching and chemical separation

Where beneficiation of ore to a very high level is accomplished on site (for example, to 'product' standard) there will usually be a need for elaborate chemical transformation of the raw materials. Processes frequently used include: leaching (usually with sulfuric acid, though reagents such as ammonia are sometimes used); solvent extraction of the leachate from a water solution to an organic (frequently 'kerosene') phase to assist in metal purification.

2.4 Cleaning mine equipment

Mobile mine equipment, such as excavators and transport vehicles, will usually accumulate ore dust. As this is mineralised material it must normally be removed by washing using water that cannot simply be released to waste. Typically wash water is stored in a special impoundment and is recycled using a pumping mechanism.

2.5 Potable uses

The main uses for high-quality water are for drinking and ablutions of mine personnel. Although water of potable standard is not strictly required for sanitary purposes, it would normally be used in the absence of severe water shortage.

3 Sources of water for mines

3.1 Rainwater stored in constructed reservoirs

Except in the driest regions, rainfall is sufficient to allow for accumulation of water in reservoirs. Typically the impoundment doubles as a sediment trap. This implies that the catchment of the reservoir is largely disturbed ground, either mineralised or not. It would be unusual for such water to be potable, but may be suitable for most other uses.

3.2 Groundwater

Whether mines require groundwater for their operations depends on the availability and reliability of surface sources. Most mines would at least supplement surface supplies with groundwater. This decision may be influenced by factors other than availability, where the withdrawal of large quantities of surface water were seen to deplete environmental flows or otherwise cause ecological damage to wetlands. Few mines would be able to store sufficient rainwater on their sites to meet all their needs. Similarly, most mines would have at least some recourse to bore fields.

3.3 Surface (stream or lake) water

If surface water is available, mines will usually seek to use it at least occasionally, even in areas of high conservation value. However unless water from this source is perennial, mines would wish to have a reliable alternative source.

3.4 Recycling

Virtually all mines recycle water. This in most cases would be due to cost considerations as much as concern for depletion of available resources. Water is often reused through many cycles, and of course this results in progressive deterioration in its quality. Typically such water is diluted or disposed of (for example to tailings) when it is no longer fit for the purpose required, or when Operational Health & Safety considerations make its continued reuse hazardous.

4 Categories of water stored by mines

The following categories of stored water are ordered by (typically) decreasing water quality.

4.1 Potable water

In general, relatively small quantities of potable water are stored on mine sites, usually in holding tanks replenished from borefields or other sources as required.

4.2 Water from sediment traps

Sediment traps range from small bunded structures to dams that may hold hundreds of thousands of cubic metres of water. They typically drain disturbed catchments and are constructed to retard the movement of erosion materials to nearby wetlands, which would increase turbidity to unacceptable levels. The quality of the water contained in sediment traps is variable, but is typically of quite good quality because the disturbed catchment material rarely contains significant mineralisation.

4.3 Water that has incidental contact with mineralised material or plant processes

Most mines are required to impound water (and sediment) that drains from sub-economic ore and the waste rock overburden that accompanies ore bodies. Open-cut mines usually produce a greater volume of waste rock than underground mines. Apart from the sediment produced by weathering and erosion, the water retained in these ponds may contain elevated concentrations of the ore species, as well as ancillary metals.

4.4 Water that has contact with ore stockpiles

Runoff from ore stockpiles can be expected to contain metals and perhaps other species at concentrations far greater than can safely be released to wetlands in raw form, except perhaps at high dilution. Depending on the identity of its constituents, chemical treatment or bioremediation may be required.

4.5 Process water

The processes that release the economic mineral(s) from its ore inevitably mobilise species which remain in depleted water solutions (raffinate) after extraction of the valuable constituents. Other entrained materials, such as organic reagents used as part of the extraction process, will usually also remain in the raffinate. The process stream will also contain large quantities of finely ground ore. The depleted ore particles, apart from containing additional, potentially toxic species that may be released later, would also contribute to turbidity if released. Process water must usually be stored indefinitely in a tailings dam.

5 Water management methods for stored water

5.1 Forced or passive evaporation

Passive evaporation is a viable means of disposal of excess water where total annual evaporation is greater than rainfall. Where this is the case (for example, mean pan evaporation in Jabiru exceeds rainfall by about 1200 mm per year) forced evaporation may not need to be used, except in unusual circumstances.

Some methods of forced evaporation include sprinkling systems that generate a fine spray, and lining the water storage impoundment with black plastic. Forced evaporation is most effective during periods when evaporation rate is greater than precipitation.

5.2 Direct release to streams or lakes

Direct (that is, untreated) release to surface water, whether deliberate, accidental or after rehabilitation has occurred repeatedly in Australia's mining history. Often the ecological consequences to wetlands have been catastrophic, such as at Rum Jungle near Batchelor in the Northern Territory, and the Mount Lyell mine in south-western Tasmania, where copper lead and acid mine drainage in particular were implicated. Environmental regulations and guidelines now stipulate more rigorously the loads and concentrations of released effluent constituents in most jurisdictions. In practice this means that only relatively benign waste waters, at high dilution, can be released in most circumstances.

5.3 Land irrigation

Land irrigation is a passive means of effluent remediation whereby waste water is pumped or sprayed onto (in most cases) a natural vegetated site. The potentially toxic components of the waste are then removed by various physical and chemical processes. The most important of these processes is adsorption onto soil particles and associated natural organic material. Land irrigation is most effective at removing heavy metals from an effluent stream and these may bind irreversibly to soil components. Heavy metals are the most important toxic constituents of many effluent streams, so land irrigation may dramatically decrease the toxicity of the water that eventually enters wetlands. Land irrigation is not effective at removing the components of waste that contribute to salinity, and may also be ineffective at removing nutrients, depending on the biological character of the irrigation area.

An obvious shortcoming of land irrigation is that the toxic components remain at the irrigated site, and may be remobilised later under some circumstances. This remobilisation may however, be at a slower rate than the original application. In this case, the release of pollutants to wetlands would be spread over a longer time.

Another shortcoming of land irrigation is that the adsorption efficiency of the site may decline progressively as active sites on soils are occupied by contaminants. It is therefore vital that the effectiveness of the irrigation area is continually monitored, to ensure that 'breakthrough' of contaminants is not observed as the ameliorative capacity of the site is exhausted.

5.4 Wetland filtration

Wetland filters are similar in many respects to land irrigation sites, but are different in that they are in most cases permanent wetlands, as opposed to dry land application sites. Wetland filters are primarily used to ameliorate low grade effluents such as urban runoff, where the primary species of concern are nutrients. As such, aquatic plants are usually important components of wetland filters, whether natural or constructed. Nutrients are removed by a number of mechanisms. Phosphorus is removed by adsorption to sediments and by plant uptake, while ammonia and nitrates are removed mainly by plant uptake, although denitrification of nitrate may occur in sediments in some circumstances. For heavy metals and organic compounds, adsorption to sediments and plant uptake may both be significant, though their relative importance has not yet been quantified. This is partly because wetland filters have not been used extensively to remediate heavy metal pollution to date.

Wetland filters suffer the same shortcomings as land irrigation in that they produce localised areas of significantly increased contamination, which may be mobilised later under appropriate conditions. They may also reach their capacity to absorb additional contaminants and must therefore be closely monitored. Where significant plant uptake of effluent components has been demonstrated, harvesting may be necessary to prevent mobilisation during plant senescence.

5.5 Water treatment

Where a mine wishes to dispose of heavily contaminated water, or less contaminated water in a region of particular environmental concern, active water treatment may be necessary. Water treatment may involve chemical or biological remediation, using a batch or flow-through reactor format. In the case of chemical treatment, a common approach is to use metal oxyhydroxides, usually generated *in situ*, to adsorb heavy metal contaminants. Activated carbon and ion exchange resins can be used to remove organic contaminants and salts respectively. Bioremediation takes many forms, including using bacteria to generate metal oxides, or to change the oxidation state of species, usually rendering them insoluble and therefore much less toxic. Sulfate-reducing bacteria can be used to produce sulfide from sulfate (in acid mine drainage for example). This process also forms alkali, so performs the dual role of fixing metals as insoluble sulfides and helping to neutralise the acid.

6 Case study: Water management at Ranger Uranium Mine

A map of the Ranger uranium mine site is given below. This shows the stream system in the vicinity of the mine and the areas dedicated to passive amelioration of chemical indicators before effluent water leaves the lease area.

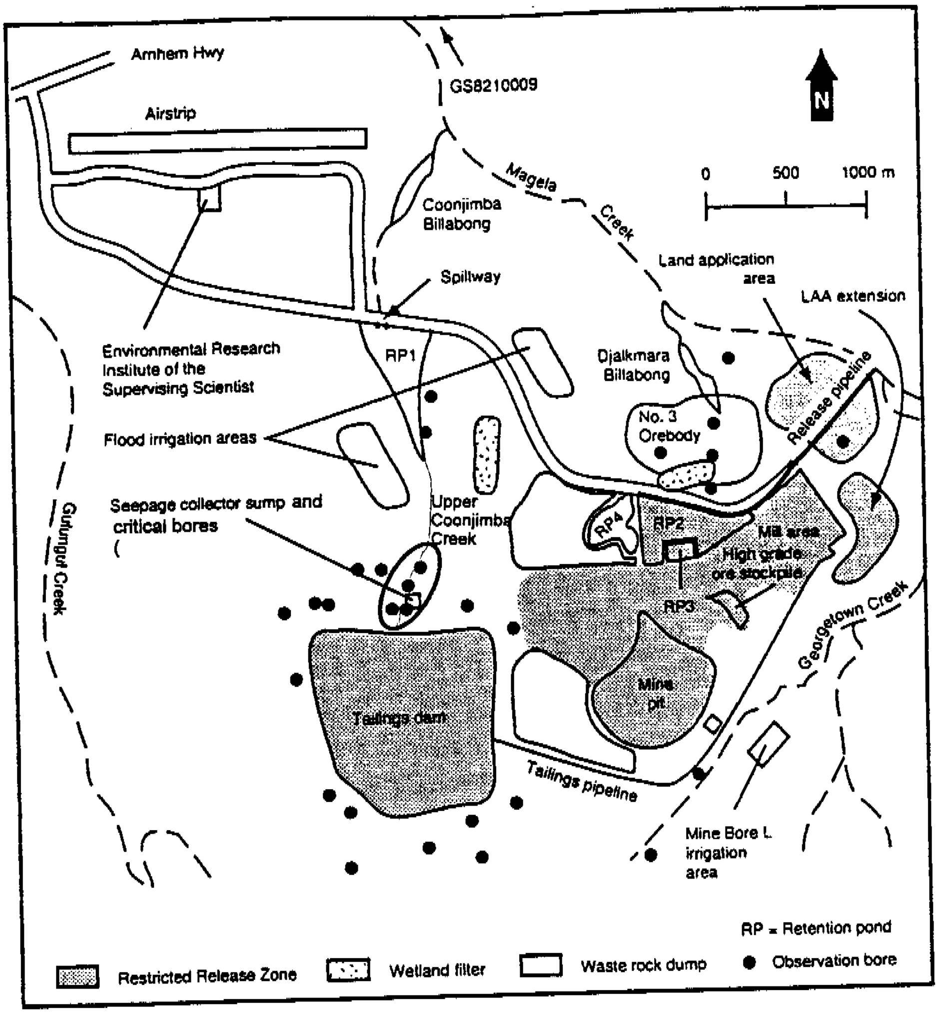

Figure 1. The immediate vicinity of the Ranger Uranium Mine

6.1 The Ranger extraction circuit

The Ranger milling operation refines the raw uranium ore to the stage of isotopically unenriched high purity oxide (U_3O_8) which is further treated overseas to reactor-suitable material. The beneficiation process at Ranger uses an acid leaching technique to separate uranium from gangue materials (waste). It does not separate minerals using flotation reagents. The detailed steps in the extraction procedure are described below. They are derived from information provided by ERA (RUM circa 1987).

6.1.1 Crushing

Ranger uses a three-stage crushing procedure. Ore is separated from waste rock by passing the ore trucks under a radiometric discriminator which measures the radiation yield from the load. This is a direct measure of its uranium content. Rock of ore grade is first crushed using a gyratory crusher followed by a two-stage short-head crusher sequence. The 'fine ore' resulting from crushing has a diameter of less than 2 cm.

6.1.2 Grinding

The fine ore is slurried with water and ground, first in a rod mill, with particles still too large being further ground in a ball mill. After grinding, 80% of the material is finer than 175 μm, and suitable for acid leaching. The grinding process adds about 1 kg of iron per ton of ore by mechanical abrasion of the grinding elements. This iron participates in the oxidation of uranium during leaching.

6.1.3 Acid leaching/oxidation

After thickening of the ground product to about 50% solids, it is leached with sulfuric acid to which is added ground manganese dioxide, the reaction taking about 30 hours. This reagent oxidises the U(IV) present in the ore to soluble U(VI) through the mediation of iron, which acts as a catalyst. The end product of leaching is a slightly acidic (pH~2) solution of U(VI), together with barren particulate matter (tailings).

6.1.4 Clarification

The turbid leach solution is clarified firstly by counter-current decantation, followed by treatment in a thickener and passage at elevated pressure through sand filters. This yields a solution with entrained solids of less than 10 mg/L.

6.1.5 Solvent extraction

The U(VI) solution, which contains many other dissolved species, is purified by solvent extraction. This process involves adding low-volatility kerosene to the water solution (the kerosene floats on the water). The kerosene contains a high molecular weight amine, and an organic modifier. This amine is converted to an organic ammonium ion by the acid remaining in the water solution, and this extracts the uranium as a sulfate complex, forming a salt in the kerosene phase.

6.1.6 Back extraction

Uranium is stripped from the loaded organic phase by extracting it with water containing ammonia, which regenerates the organic amine and transfers the uranium, as uranyl sulfate, to the water phase.

6.1.7 Precipitation

Precipitation of the uranium as ammonium diuranate (yellowcake) is achieved by adding ammonia to the solution until the pH reaches 7.6. The precipitate is thickened to remove excess water, then centrifuged.

6.1.8 Calcination

The final product, U_3O_8 is produced by heating the yellowcake to 700°C in a multihearth furnace. This product is dark green.

A simplified flow chart of the operation is shown below.

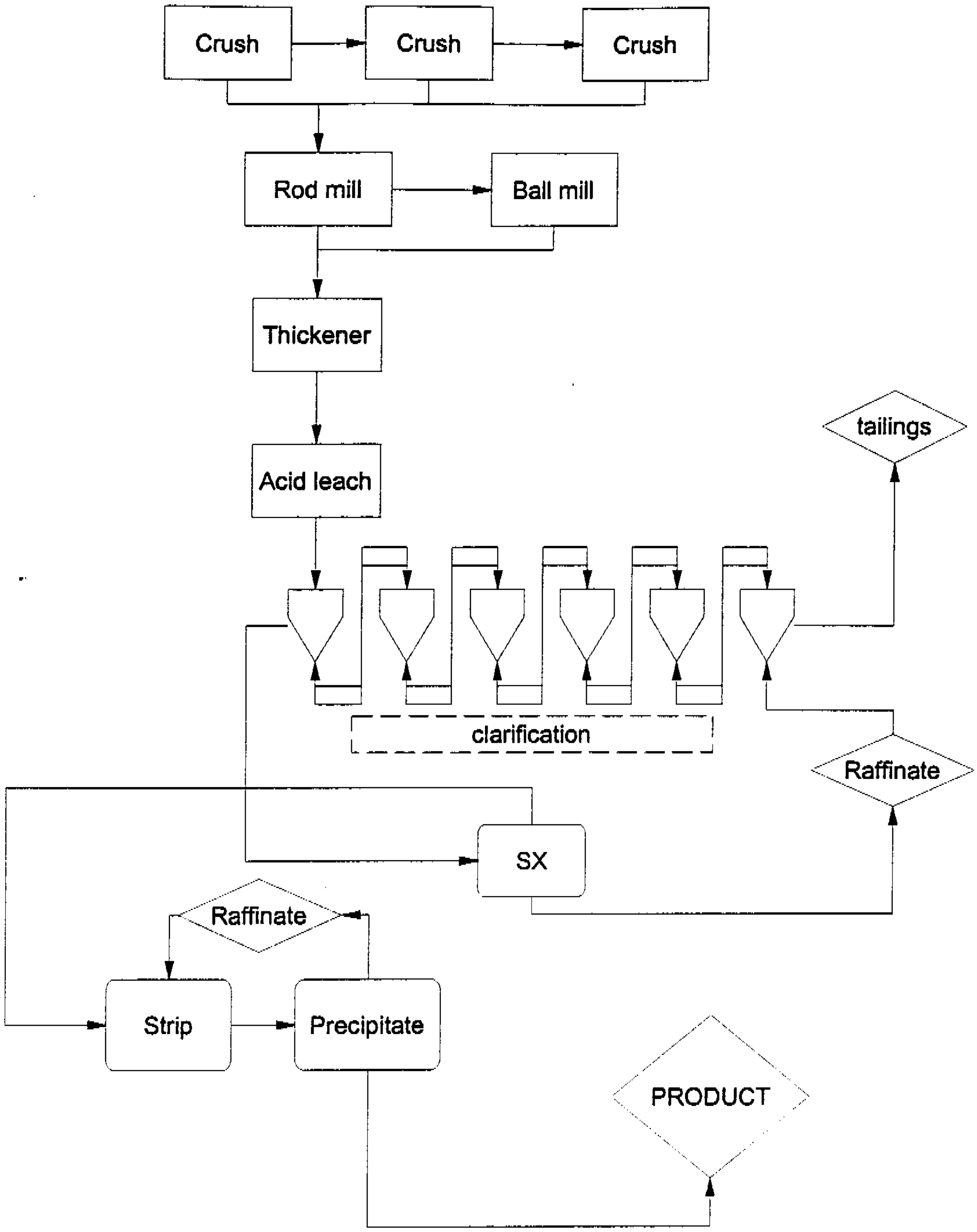

Figure 2. Simplified flow chart of the Ranger Extraction Circuit

6.2 Sources of water at Ranger

- Retention ponds 1, 2 and 4
- Brockman borefield
- Magela Creek

Water is removed preferentially from RP2 for mill purposes. In most years Ranger has surplus water stored in retention ponds (catchment area ~660 ha; evaporative surface ~150 ha) so the borefield and Magela Creek do not usually need to be drawn upon.

6.3 Water management at Ranger

Water management at Ranger is based on two principles

- There will almost always be surplus water to dispose of on an annual cycle.
- Movement of water around mine circuits results in quality degradation and more restrictive disposal options.

Disposal options are regulated, generally according to water quality.

6.4 Disposal Mechanisms at Ranger

6.4.1 Unrestricted direct release to the environment

Good quality water (usually potable) is released by free egress to Magela Creek. The most important example of this is RP1 water. RP1 was designed as a sediment trap, and although the water it contains has slightly elevated solute concentrations, these do not pose an environmental hazard. RP1, being a relatively mature system, operates as a wetland filter and removes about 10 t of sulfate per year. About 1 000 000 m^3 of water is released from RP1 passively each year.

6.4.2 Restricted direct release to the environment

Water of higher solute content, but low uranium concentration (typified by RP4) can also be released, but regulatory approval must be received, subject to certain hydrological conditions in the creek. Although this water can be released directly to Magela Creek, current practice is to release it into a backflow billabong, which as acts as a wetland filter to remove the small quantity of uranium present.

6.4.3 Release to the environment after passive treatment

Water of similar solute concentration to RP4, but much higher concentrations of uranium and manganese (typified by RP2), can in practice not be released directly to the environment, but must first be 'ameliorated' using either land application, passage through a wetland filter (which removes manganese and most of the uranium), or increasingly, a combination of both.

6.4.4 Water removal by evaporation

Process water is of extremely poor quality. This contains very high concentrations of solutes, some heavy metals and radionuclides, and entrained tailings, and must be completely retained on the mine site, mostly in the tailings dam and Pit 1. The only present means of disposal of this water is by evaporation. Some techniques of enhanced evaporation have been investigated.

6.4.5 Active treatment of waste water

Very wet seasons (such as 1996–97) can precipitate a water management crisis. This has encouraged ERA to investigate methods of active water quality management. Several water-treatment methods are under consideration, both biotic and abiotic, which would probably involve a reactor-based format. One reactor design of potential interest to ERA is the use of manganese-oxidising bacteria to produce oxide particles of high surface area that can be used to adsorb radionuclides such as uranium and radium. The likely mechanism of adsorption is cation exchange, whereby negatively charged sites on the oxide surface are occupied by positively charged radionuclide ions. ERA is also supporting a project which uses sulfate-reducing bacteria to fix sulfate in effluent streams as insoluble sulfide minerals. This technology may ultimately be deployed in a reactor format.

6.5 A simple water balance at Ranger mine

The total area of 'general catchments' within the Ranger lease is about 6 590 000 m^2. This corresponds to the disturbed area in the immediate vicinity of direct mining and milling operations. It does not include the Pit 3 area which is currently being developed by ERA. The quality of rainwater after contact with these catchments is highly variable; some can only be disposed of by evaporation while some has effectively free egress to Magela Creek.

The following parameters apply to the mine site.

Mean annual rainfall at Jabiru Airport (1971–1997): **1457 mm**

Mean annual evaporation at Jabiru Airport (1971–1997): **2625 mm**

Of the total 6 590 000 m^2 surface area, about 1 500 000 m^2 is standing water, which has an evaporation coefficient (based on RP1) of 0.92 (this is the ratio of observed evaporation to that predicted from pan evaporation values). Evaporation from areas not inundated is approximately 0.80 of that predicted from pan evaporation (based on the RP1 catchment) while they are wet. The catchment of RP1, net of the pond, (2 100 000m^2) is vegetated and thus has greater water retentive properties (and hence greater evapotransporation) than the unvegetated areas of the site, but will suffice for this example. It is assumed that water evaporates from ponds all year, but from land areas only during December–April, when they are wet. The mean evaporation from December–April inclusive is 930 mm.

In an average year, approximately:

$$\mathbf{6\,590\,000 \times 1.457 = 9\,600\,000\ m^3}$$

of rain falls on the Ranger site, of which about **930 000m^3** flows over the RP1 weir.

Evaporation from standing water is:

$$\mathbf{1\,500\,000 \times 2.625 \times 0.92 = 3\,620\,000\ m^3}$$

Evaporation from 'dry' areas is:

$$\mathbf{5\,090\,000 \times 0.93 \times 0.80 = 3\,900\,000\ m^3}$$

Therefore the mean loss of water from the Ranger site is:

$$\mathbf{930\,000 + 3\,620\,000 + 3\,900\,000 = 8\,450\,000\ m^3}$$

This leaves about <u>1 000 000 m^3</u> of surplus water, which is disposed of by a variety of land application methods, augmented by direct release in most years. Some water is also lost by seepage from the various impoundments though this is relatively minor.

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Tourism and fishing in Kakadu National Park

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Greg Miles has worked as a ranger and unofficial Park naturalist in Kakadu National Park since 1974, acquiring an invaluable knowledge of Kakadu and its wildlife. He is now Public Relations officer for the park. His position embraces a mixed bag, including media contact, management of film and photo crews, public presentations and training for tourism, staff, catfish and pythons!

Key words: Kakadu National Park, Aboriginal land owners, wetlands, tourism, fishing

1 Contemporary historical overview

The size of Kakadu National Park is such that different regions experienced differing historical processes. The following information relates particularly to the north eastern sector of the Park.

Until the beginning of the 1970s the Alligator Rivers Region (ARR) was one of Australia's most poorly known regions. Following failed attempts at resettling army personnel after the two World Wars, the region slumped into a quiet existence populated almost exclusively by the traditional Aboriginal people of west Arnhemland. Recognition of Aboriginal occupancy of the area goes back a long way. In addition to the establishment of Arnhemland in 1931, the Woolwonga Aboriginal Reserve, centred on Nourlangie Camp in Kakadu, was established in 1936.

In 1965 the then Reserves Board of the Department of the Northern Territory (the precursor of the Parks and Wildlife Commission of the Northern Territory) proposed a national park in the region. So impressive was the landscape that Mr Joe Fisher, an early mining prospector, lent weight to the concept of several small parks being proclaimed. Indeed it was the activities of mineral prospectors that first uncovered the presence of uranium, initially in modest quantities in the South Alligator River catchment, and later the large reserves of uranium ore under the northern sector of the ARR. These northern discoveries were of such note that the Commonwealth set up a multidisciplinary study designed to examine a wide range of issues which were poised to profoundly affect the future of the region. Accordingly, specialists in the fields of mining, anthropology, archaeology, zoology, pastoralism and national parks combed the region as part of a major and concentrated resource inquiry named the Alligator Rivers Region Environmental Fact Finding Study.

2 Tourism then

Prior to the mid 1970s, limited access to the Park area and the perceived boring nature of the lowland forests served to direct 'tourists' to the wetlands, with a few visiting the art sites at Ubirr, Nourlangie and Deaf Adder Valley. Then, as today, the real ecological 'action' in the region was on the floodplains and in the billabongs. In addition to spectacular scenery and relative ease of travel, on the fringes of the plains 'tourists' could easily satisfy their blood lust by shooting pigs and ducks, catch piles of barra and have a cool-off swim in the rivers and billabongs. Buffalo were a common vertebrate feature but were classified as stock and the bread and butter beast of the pastoral properties of Mudginberri and Munmarlary. Poaching of buffalo by pet meat shooters and barramundi by illegal gill-netters was common practice in the late 1960s and early 1970s. Saltwater crocodiles were rare in the area, having been hunted to near extinction. Saltwater crocodiles became a protected species in 1972.

Also in 1972, the Alligator Rivers Wildlife Sanctuary was declared under Commonwealth Department of Northern Territory legislation. This was to become the nucleus and first stage of Kakadu in 1979. The role of the first five Alligator Rivers Rangers, appointed in 1972–73, was much to do with chasing and catching these (often aggressive and hard core) poachers.

In concert with the push for mining, land rights and the declaration of the Park, the construction of the Arnhem Highway, which was completed in 1974, was the conduit to increased tourism in the area. Also feeding this growth was the publication in 1973 of the results of the Alligator Rivers Fact Finding Study, which began to catalogue the extraordinary richness of the mineral, natural and cultural assets of the region.

Government-initiated public exposure during the late 1970s featured natural values, especially wildlife and landscapes. A major media push by the then Australian National Parks and Wildlife Service was designed to solicit support for the declaration of Kakadu National Park by Federal Parliamentarians. This extensive and successful campaign featured beautiful imagery of the region which, in no small way, captured the imagination of many mainstream Australians.

During the early 1980s, sudden and prominent media growth occurred in the national debate concerning mining, conservation, land rights and states' rights issues intellectualised tourism in the Alligator Rivers. Visitors were very much interested in these debates as well as the beauty of the region. This was exemplified by the arrival of hunters carrying cameras rather than rifles. Growth in tourism was proportional with the national media interest in the region. People were excited at the prospect of visiting a remote area only just giving up its secrets.

3 Tourism today

Tourism in Kakadu today is multi-faceted with important seasonal variability. Not only does the season affect access and things to do, but it also changes the type of visitor. A 1993 survey indicated that during the Dry season 67% of all visitors were from interstate in Australia, with only 28% being from overseas. During the Wet this ratio was reversed, with 64% being from overseas whilst a modest 22% came from interstate. The same survey indicated that people came primarily to see spectacular wilderness landscapes. Other important reasons to visit were to see wildlife and Aboriginal rock art. In 1993 less than 20% came primarily to catch fish.

Visitor numbers to Kakadu in 1996 were about 220 000. These numbers represent a continued levelling off, or decline, in comparison to the dramatic rise in visitor numbers experienced in the mid to late 1980s.

Until 1989 the natural environment was promoted as being the jewel in Kakadu's crown. In that year the Kakadu Board of Management, with an Aboriginal majority, was formed. Since that time the cultural values of the Park have taken precedence in promotion strategies. The emphasis on the indigenous culture of the Park is reflected in the 1997 Kakadu Draft Plan of Management.

The wetlands of Kakadu are inscribed on the Ramsar list of Wetlands of International Significance. In recognition of the importance of these wetlands, the Park offers 19 discrete destinations which principally interpret this landform. A further 4 localities include the wetlands as a secondary message. Feature tourism activities in the wetland environment in the Park include two boat cruises, one viewing platform and several nature trails. The Bowali Visitor Centre and the Warradjan Aboriginal Culture Centre emphasise the significance of the wetlands both from the points of view of a tourism wildlife extravaganza and as a resource rich homeland for Aboriginal traditional owners.

The establishment of tourist facilities within the Park have been achieved through a joint management process involving the Aboriginal owners and Parks Australia North. The Mamukala viewing platform and nature trail provides a case study. The completion of the Arnhem Highway in 1974 provided rapid, all-weather access to productive floodplains. This access was valued by local Aboriginal hunters as well as the parks service. Both parties wished to gain access to the Mamukala area via the nearby Arnhem Highway. Bipartisan use of the area was not possible as much of this Aboriginal activity involved hunting geese with shotguns and therefore public safety was a paramount consideration. In 1986, Parks Australia initiated negotiations with Aboriginal owners and residents. An agreement was struck. Aboriginal traditional owners accepted the exclusive use of the Mamukala area by tourists in exchange for another wetland to the north of the highway. Parks Australia agreed to zone this northern wetland exclusively for their use. This agreement has successfully endured since 1987.

4 Recreational fishing

Recreational fishing in Kakadu is almost a single species exercise. Apart from Barramundi there is some limited pursuit of Thread-finned Salmon, Jew Fish and miscellaneous reef-fish offshore. There is also some minor interest in catching Saratoga on flys. The prime season for Barramundi fishing in the Park is the March to May period when fish can be caught in good numbers along the edges of floodplain gutters which drain the plains into the South Alligator and East Alligator Rivers. Closed water (billabong) fishing is popular all year and fish can commonly be caught in more than 13 important and discrete water bodies.

All nets, other than landing and mosquito nets, are banned in the Park as is the use of live bait. Crab pots are also a banned item, effectively making all types of crabbing illegal. Fishing upstream of the Kakadu Highway is prohibited with the exception of Muirella Park and Sandy Billabong on Nourlangie Creek. The entire catchment of the West Alligator River is closed to all fishing thus providing one complete river system without any fishing pressure.

Aboriginal people are enthusiastic anglers who generally use less sophisticated tackle than that carried by non-Aboriginal anglers. The traditional palate also enjoys a wider range of table fish, including such species as Saratoga (commonly speared), most species of grunters, Salmon and Eel-tailed Catfish, Sleepy Cod and river sharks.

During the past two decades recreational fishing was a more significant activity in relative terms than it is today. The change has not been due to a withering of interest in fishing, but due to the mass arrival of commercial tourism carrying people who either do not have the time or the interest to fish. Despite the relatively small numbers of visitors fishing, this group of park users are enthusiastic and vocal about their sport.

Park management and the Aboriginal traditional owners recognise recreational fishing as a legitimate activity in the Park. At the same time Parks Australia North and the Board of

Management recognise the need to manage recreational fishing in a way which is commensurate with the philosophy and objectives of a national park. It is for these reasons that commercial fishing was progressively phased out of Kakadu, ending in the late 1980s.

The changes proposed to fishing in the 1997 draft Kakadu Plan of Management also reflect park management philosophies and have proven to be highly controversial. Draft proposals include:

- A ban on fishing in the East Alligator River upstream of the upstream boat ramp.
- Access down the South and East Alligator Rivers to be regulated by permits.
- A bag limit of two Barramundi per person per day.
- A ban on fishing competitions.
- A review of fishing activities on Yellow Water.

Numerous public submissions as well as direct representations concerning angling were made to the Board. Many respondents were disconcerted to find that any fishing is allowed in Kakadu. They argue that all the wildlife should be protected in national parks. These people would argue that the more than $1.5 million dollars that Parks Australia has committed to boat ramps and fish cleaning facilities for anglers has been misspent. However, the overwhelming number of public submissions argued strongly for the easing of current restrictions on fishing in Kakadu or at least a maintenance of the status quo. As a result of this public response the Board has devoted considerable time to the issue of recreational fishing and has fully explored all options. The results of the Board's deliberations will be made public with the release of the final Plan of Management early in 1998.

5 Issues affecting tourism and fishing on the wetlands of Kakadu

Tourism on wetlands can pose environmental problems which warrant investigation. Several examples and titles of associated studies are listed below.

1. Dry season traffic visiting Twin Falls must cross the upper reaches of Jim Jim Creek. This results in a turbidity problem which persists for a kilometre downstream. A study entitled *Effects of suspended solids on stream biota downstream of a road crossing on Jim Jim Creek, Kakadu National Park* has recently been completed by ***eriss***.
2. An analysis of the environmental, social and economic compromise options for sustainable operation of a tour boat venture in Kakadu National Park was conducted by CSIRO and the Northern Territory University.
3. A study of the impact of recreational angling on numbers of Barramundi, entitled *An assessment of the Barramundi and Saratoga population of Yellow Water Billabong, Kakadu National Park, 1995 and 1996* was conducted by the Fisheries Division of the Northern Territory Department of Primary Industry and Fisheries.

Other management issues include (but are not limited to):

- The threat of the spread of weed seeds on vehicles and machines such as those driven into the Park by tourists, earth moving contractors, pig contractors and others.
- Soil erosion associated with the use of unsealed roads and tracks.

- Prescribed burning and dealing with late season wildfire. This can be complicated by the presence of campers situated on unburnt floodplain grasses.
- Late season wildfires originating from lightning strikes and other sources.
- Safety issues such as interactions between anglers and crocodiles and boating safety in hazardous tidal rivers.

6 The future

The future of tourism depends in no small part on how the issues under discussion during this workshop are dealt with and include:

- The proliferation of weeds such as Para Grass. The arrival of new weeds such as Gamba Grass, Mission Grass, Alemon Grass and Humidicola
- Containment of *Mimosa pigra* and feral pigs
- The long term future of buffalo
- Burning floodplains the 'right way' in a changed environment
- Perhaps most importantly, the arrival of *Bufo marinus* (cane toad).

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Weed management on wetlands of Australia's Top End

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Abstract

Weeds (plant species growing where they are not wanted) are spreading faster than they can be controlled in Australia. Despite this, new plants with the potential to become weeds are continuing to be introduced into the country. Northern Territory wetlands are relatively free of weeds, but are intrinsically prone to weed invasion, and this is particularly so for the vast Top End floodplains.

Top End wetlands represent an important part of Australia's biodiversity and are very important culturally for Aboriginal people. Weed invasions often have the effect of replacing the varied native vegetation of the floodplains with an extensive monoculture. Consequently, in areas of weed invasion, there is a massive reduction in biodiversity.

This paper describes some ecological and socio-economic reasons for the vulnerability of Top End floodplains to the invasion by weeds and makes suggestions on ways of improving the management of the weed threat.

Keywords: weeds, wetlands, biodiversity, weed management strategy

1 Introduction

Top End wetlands are some of the most extensive and inaccessible in the country and are generally in reasonably 'good' condition (Storrs & Finlayson 1997). These wetlands include seagrass beds, salt marshes and mangrove swamps in addition to the large, seasonally inundated, freshwater floodplains and their associated seasonal or permanent waterbodies. Vast floodplains, especially in the north-west corner of the Territory that receives the most rain, are associated with the major river systems of the Top End (Storrs & Finlayson 1997).

It is the floodplains that I will concentrate on in this paper. They are, arguably, the most biologically significant of all the wetland types and are a focus of human activity. There are about 10,000 sq km of floodplains in the Top End and one of their greatest immediate threats is invasion by weeds (Storrs & Finlayson 1997).

Top End wetlands represent an important part of Australia's biodiversity and are a source of traditional foods and medicines for Aboriginal people. Aboriginal people continue to be reliant on the natural environment for both their spiritual and physical well-being (Pearce et al 1996). Practices such as hunting and foraging have an important place in contemporary Aboriginal life and wetlands are a focus of this activity (Russell-Smith et al 1997).

In the Top End, floodplains undergo dramatic seasonal changes in water depth – from completely dry to depths of several metres in the Wet season. The water is warm to hot and nutrient concentrations vary seasonally, though generally are not particularly high (Walker & Tyler 1984). However, plant productivity is very high, particularly during the Wet season (Finlayson 1988). It is interesting to note that the flora is neither particularly diverse nor unique and species of plants found on floodplains are largely cosmopolitan. However the outstanding feature of the floodplain vegetation is its seasonal variation in floristic composition (Sanderson et al 1983, Finlayson et al 1989, Rea & Ganf 1994). This extreme seasonal variation of habitats, together with the high productivity of plants leads to very high numbers of animals particularly birds, fish, mammals and crocodiles (Finlayson et al 1988; Rea & Storrs 1998).

2 What is a weed?

A weed is a plant that is growing where it is not wanted (Cowie & Werner 1988). In the Top End, some plants are considered weeds by all land users (eg mimosa and salvinia), while other plants (eg introduced pasture grasses) are considered weeds by some land users (tourism operators, conservationists, anglers), but not by others (eg pastoralists) (Rea & Storrs 1998).

3 The weeds of concern

Throughout Australia weeds are spreading faster than they can be controlled and plant introductions to Australia are likely to occur with increasing frequency (Rea & Storrs 1998). Talking in species numbers, the Northern Territory is relatively free of weeds, with only 5–6 per cent of its flora listed as alien (Humphries et al 1991). This compares favourably to an Australian average of 18 per cent (W.M. Lonsdale pers comm). Reasons for the low percentage of weed species might include limited agricultural development, low population densities (Humphries et al 1991), seasonal aridity (Usher 1988), and the low fertility of many northern Australian soils (Cowie & Werner 1993).

Low population densities and limited agricultural development add to the common perception that the ecological condition of Top End wetlands is pristine. However, the invasion of feral animals and improved vehicle access followed by pastoralists and other wetland users has often been associated with the invasion of weeds (Storrs & Finlayson 1997).

There are a number of weed species currently threatening Top End wetlands. The three most invasive species are the spiny central American shrub *Mimosa pigra* (mimosa) (Lonsdale et al 1995), the free-floating South American aquatic fern *Salvinia molesta* (salvinia) (Storrs & Julien 1996) and the African pasture grass *Brachiaria mutica* (para grass) (Smith 1995).

In neighbouring savanna woodland (lowland) areas the major invasive weeds are tall, vigorous, perennial grasses such as *Pennisetum polystaschion* (mission grass) and *Andropogon gayanus* (gamba grass). These introduced grasses alter fire regimes by increasing the number of hot, late Dry season fires. Over time, the number of trees are reduced resulting in a change from woodland into grassland (Smith 1995).

3 The weed threat

Weeds have the effect of replacing the floristic, spatial and temporal variation (that are so important for maintaining diversity) with uniformity (Rea & Storrs 1998). Consequently there is a massive reduction in biodiversity.

It is a basic principle of weed management that weeds invade areas that have been disturbed. The more prolonged, repeated or intense the disturbance the more weeds are likely to invade (Hobbs 1991). Apart from the continuous colonisation and retreat of native species due to the seasonal changes in water depth, the floodplains are also prone to fire, wind storms and cyclones. Thus Top End floodplains are subject to a high level of natural disturbance making them intrinsically susceptible to weed invasion (Rea & Storrs 1998).

It is something of a paradox then that it is the extremely dynamic nature of the Top End wetlands that creates their biodiversity, but also makes them susceptible to weed invasion. If this is not enough, non-Aboriginal people have introduced foreign disturbances to the system. Until recently, the main disturbance was the Asian water buffalo (*Bubalus bubalis*), a large feral animal.

Buffalo escaped the first ill-fated European settlements in the north around 150 years ago. By the late 1800s the buffalo population supported a large hide industry that lasted through to the 1950s. In 1985 the feral buffalo population in the Top End was estimated to be 341 406, about the same size as the domestic cattle herd, with densities on floodplains exceeding 7 animals/km^2 (Bayliss & Yeomans 1989). Damage to the wetlands was substantial with large areas denuded of vegetation and levees broken down, allowing premature drainage and saltwater intrusion (Finlayson et al 1998).

During the 1980s numbers of buffalo were reduced to low levels mainly as a result of the Commonwealth's Brucellosis and Tuberculosis Eradication Campaign (BTEC). Following buffalo removal, the recovery of vegetation and amelioration of land degradation has been dramatic (East 1990, Skeat et al 1996). However, during this period of large scale disturbance many weed species were able to colonise. Further, disturbance by feral animals remains a problem because as the buffalo population decreased, the pig population increased. After the removal of buffalo at CSIRO's experimental station in Kakadu National Park, pig numbers were observed to double (Corbett 1995). The absence of effective control measures for pigs and associated wetland disturbance is cause for concern.

Even intensively managed conservation areas are at risk of weed invasion. The number of alien plants in Kakadu National Park has increased at the rate of 1.6 species per year since 1948 (Cowie & Werner 1993), and this trend is expected to continue as a result of disturbance through increased tourism and development. In their survey of Kakadu National Park Cowie & Werner (1988) found that most of the naturalised alien species were associated with human activity such as roadways, borrow pits, settlements, campgrounds and other disturbed areas, but in addition, habitats adjacent to floodplains and creeks were also found to be heavily invaded by weeds.

The economy of the Northern Territory is still in a vigorously government-encouraged development phase and is based firmly on exploitation of natural ecosystems and resources. It is often stated that the land uses most capable of integration on the floodplains are conservation, tourism, recreation, commercial wildlife harvesting, and non-intensive pastoralism (Whitehead et al 1990). However, the Northern Territory Government places great emphasis on agriculture with some agencies seeing intensification of pastoral activities as a priority. This is even though expenditure by tourists is four times the gross value of the pastoral industry (Whitehead et al 1990) and introduced pasture grasses can have a profound effect on the tourism industry by decreasing the wildlife visitors come to see (Lonsdale 1994).

Para grass, which has been used by the pastoral industry for many years, has shown a great capacity to invade wetland areas, but is still being introduced to new sites with government encouragement (Rea & Storrs 1998). Also worrying to wetland managers, is that the Northern Territory Government is encouraging the use of two other improved pasture grasses from South America, *Echinocloa polystachya* (aleman grass) and *Hymenachne amplexicaulis* (olive hymenachne) (Lemcke 1996). These species have been shown in Queensland to smother native vegetation by forming dense and extensive monospecific stands (Clarkson

1995). Both grow in deeper water than para grass, and olive hymenachne, in particular, is a prolific seeder. Currently there is a moratorium on their use in Queensland. Continued introduction in the Northern Territory ignores advice about their weedy potential and flies in the face of agreements to which the Northern Territory Government is a signatory (Rea & Storrs 1998).

4 Strategic weed management

Expansive natural areas combined with small human populations necessitates a strategic approach to tackling the weed issue. The Northern Territory Government has recently developed a weed management strategy (Northern Territory Government 1996) that calls for government to work with landholders and land managers to plan and implement weed management.

A weed management *strategy* entails careful planning and directing the large-scale, long-term operations of a weed management program on a catchment basis (Moody & Mack 1988). Area management rather than species management should be the focus. The philosophy of any weeds management strategy should be to establish why weeds are present and address those causes, rather than killing weeds *per se*. Storrs & Lonsdale (1995) and Storrs et al (1996) present a series of steps that should be addressed in a weed management strategy. These are discussed below.

4.1 Prevention

One of the most powerful weapons against weed incursions is prevention. In Australia it is often the case that weeds are allowed to invade. Plants that have become weedy were, on most occasions, introduced intentionally for other purposes (Panetta 1993). Mimosa, salvinia and 'improved' pasture grasses are all deliberate introductions that have become major environmental weeds.

Ecological Risk Assessment should be mandatory for all proposed plant introductions to Australia or between Australian biogeographic regions. Controlling importation can also cover intrinsic measures such as quarantining of areas and providing stock and vehicle wash-down facilities. Large areas of the Top End, such as Arnhem Land, are free of many invasive species and the desire would be to keep them that way. Education and awareness programs would help in the establishment of changes to current management practices, as would effective liaison and cooperation between agencies.

4.2 Surveillance and early intervention

Surveillance and early intervention is another powerful weapon against weed invasion. There is a need to identify sites at risk, which are generally areas of high disturbance through natural, human or feral animal activity. Rangers and others need to be trained in the identification of weed species and programs need to be developed to routinely survey high risk sites. The value of early intervention was highlighted at Maningrida in the early 1990s when a senior Aboriginal land owner recognised mimosa from a Northern Territory Government poster. He was able to lead authorities to the 0.3 ha plot which was swiftly dealt with.

4.3 Identify habitats that are prone to invasion

In the Top End, wetlands and riparian systems are the natural areas most prone to weed invasion. In fact, all the critical (highly invasive) weed species identified by Humphries et al (1991) are either restricted to floodplain habitats or form their most dense infestations along water courses. Emphasis should therefore be placed on weed management of these habitats.

4.4 Decreasing an area's susceptibility to invasion

There is a need to minimise disturbance and rehabilitate disturbed areas (Hobbs & Huenneke 1992). Developmental activities such as road building should be undertaken in a way to minimise impacts on the environment. There is also a need for a coordinated approach to the control of feral animals. In Arnhem Land, buffalo were largely disease free so BTEC control in this area was limited. Pig control is largely *ad hoc* and ineffective. Another important aspect of decreasing an area's susceptibility to weed invasion is to rehabilitate disturbed areas using competitive native species.

4.5 Managing existing weeds

Invasive weeds may already exist in a region. A prerequisite for a weed management program is a detailed survey of the area to highlight the critical invasive species and the key parts of the landscape they threaten, and to prioritise resources accordingly.

It is necessary to develop a weed management structure to coordinate such activities. Physical, chemical and biological control, the manipulation of fire regimes and promoting native plants; all should play a part. The work might involve a species specific approach using biological and chemical control for highly invasive species but also, as far as possible, habitat management using a range of techniques such as feral animal control, visitor and fire management and the revegetation of disturbed areas (Storrs 1996). This work should include Ecological Risk Assessment of the impacts of control measures such as the use of herbicides.

5 Development of a weed management strategy

A weed management strategy for a specific locality should be integrated with the Northern Territory Weeds Management Strategy (Northern Territory Government 1996) and the National Weeds Strategy (Commonwealth of Australia 1997). In developing a weed management strategy for Kakadu National Park (Storrs 1996) the following steps were taken:

5.1 Research phase

A literature review of environmental weed management in Australia and elsewhere was used to determine the current state of knowledge and identify objectives.

5.2 Consultation phase

Meetings were held with Aboriginal traditional owners, rangers, representatives of Aboriginal associations, government agencies, the tourism industry and weed control professionals. These consultations determined the main issues, needs and priorities in regard to weed management in Kakadu National Park.

5.3 Draft overview paper

Next a draft overview paper was prepared. This developed a conceptual framework for weed management and covered:

1. main sites of weed infestation in Kakadu National Park and the prioritisation of major weed species;
2. responsibilities and relationships between different organisations involved in weed control;
3. current weed management programs;
4. habitat management objectives such as the minimisation of disturbance and the rehabilitation and revegetation of disturbed sites;
5. strategies for preventing the introduction of new weeds;
6. procedures for early intervention in cases of new weed incursions;
7. training, staffing, resource and research needs; and
8. performance indicators.

5.4 Further consultation and development of the strategy

The draft overview paper was circulated widely for comment and further consultation undertaken. The extensive consultation was undertaken to embody the state of current knowledge and opinion within the strategy and to ensure ownership of and support for the document and directions. These actions combined provided the basis for the strategy.

6 Conclusion

Wetlands of the Top End are relatively pristine, however the invasion of weeds is and will continue to be a real threat. The vast size of the Top End and the relatively small population mean that it is necessary to take a strategic approach to tackling the weed issue. Once the planning process is completed, it is necessary for government, conservation agencies and land owners to work together and provide the resources to ensure that strategic weed management can be carried out.

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The management of *Salvinia molesta* in Kakadu National Park, Northern Territory, Australia

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Abstract

Kakadu National Park, listed as a World Heritage Area, is the jewel in the crown of Environment Australia's national parks. Kakadu National Park is dominated by two major river systems, the East Alligator and South Alligator Rivers and their associated tributaries and floodplains. These huge wetlands are very important to the ecology of the area and played a large part in securing the park's World Heritage Listing. They are also listed by the Ramsar Convention as 'Wetlands of International Importance'.

The rampant floating aquatic weed, *Salvinia molesta* (salvinia), was discovered in Kakadu National Park in 1983. It was decided to rely on biological control rather than attempt to eradicate the weed due to the large extent of the existing infestation and successes with the biological control agent, a weevil, elsewhere in Australia. Although the weevil appeared to give good control in early years, there was a huge build-up in salvinia in the late 1980s that resulted in the complete coverage of most billabongs in the Magela Creek system for more than 2 years. This build-up prompted the Australian National Parks and Wildlife Service (now Parks Australia) to contract the CSIRO Division of Entomology to investigate the situation and suggest measures to improve control.

This paper presents a background to the salvinia problem and an account of salvinia management in Kakadu National Park.

Keywords: *Salvinia molesta*, chemical and biological control, Kakadu National Park

1 Introduction

Compared to the rest of Australia, Kakadu National Park has relatively few weed species (Storrs & Lonsdale 1995, Storrs 1996). However it does have a number of invasive weeds (ANPWS 1991), one of the most notable being the aquatic weed *Salvinia molesta* (salvinia) (Holm et al 1977, Mitchell 1978). Salvinia was first reported in Australia in 1952 but was not discovered in Kakadu National Park until 1983 (Finlayson 1984a).

Salvinia is a floating fern that is native to a restricted area in south-east Brazil; a sub-tropical zone at a latitude that equates with the area from northern New South Wales to southern Queensland in Australia. It is believed that salvinia was originally exported as an aquarium or pond plant and has since invaded tropical wetlands throughout the world. It is a sterile plant that reproduces vegetatively. Under ideal conditions and away from its natural enemies it has a phenomenal growth rate and can double its dry weight every 2–3 days (Finlayson 1984b) although the fastest growth rate recorded in Kakadu National Park was a doubling of dry weight in 5–7 days (Storrs & Julien 1996).

Chemical and physical methods were initially used in attempts to control salvinia in the Northern Territory and, in a limited number of cases where infestations were well contained, successful eradication was achieved (Miller & Pickering 1988). It is important to note however, that review papers from the late 1970s state that, despite considerable effort to control and eradicate salvinia, no single satisfactory solution had emerged (Finlayson & Mitchell 1982).

2 Biological control of *Salvinia molesta*

In the early 1980s, CSIRO Division of Entomology had major successes with a biological control agent on infestations in Queensland (Room et al 1981). The agent was a small weevil, *Cyrtobagous salviniae*, discovered in the home range of salvinia, in south-east Brazil (Room et al 1981, Calder & Sands 1985). The adult weevil feeds on the new buds preventing growth from that point. However, the real damage is caused by the larvae as they burrow through the rhizome of the plant causing the plant to become friable and waterlogged to the point where it eventually sinks and drowns (Sands & Schotz 1985).

In trials in Queensland, the level of control by the weevil was dramatic. On a 400 ha infestation on Lake Moondarra, weevils reduced the infestation to just 4 ha in 18 months, that is 1% of its former size. In the process the weevils had destroyed 8,000 tonnes of salvinia (Room et al 1981). The weevil has since been exported to other areas of the world and has proven to be one of the most successful biological control agents to date (Storrs & Julien 1996).

3 *Salvinia molesta* in Kakadu National Park

In 1983 salvinia was found in the Magela Creek, a tributary of the East Alligator River (Finlayson 1984a). As the salvinia infestation was considered too extensive to eradicate, it was decided to rely on the newly discovered biological control agent (Storrs & Julien 1996).

Weevils were first introduced into the Magela Creek system in late 1983 and further releases were made in 1984/85. Once established, weevils spread and seemed to provide reasonable control in the early years, though evidence for this is anecdotal (Storrs & Julien 1996). In later years (1987–1991) however, control was unsatisfactory with salvinia expanding and completely covering billabongs. Some billabongs were covered for more than two years at a time with a thick layer of salvinia which was subsequently colonised by grasses, sedges and even small trees to form a sudd (Julien 1990, Skeat 1990).

Salvinia is considered detrimental because it can alter aquatic ecosystems and change the distribution of native plants and animals. In Kakadu National Park, it also restricts the use of waterways for food gathering by Aboriginal traditional owners and impacts on recreational fishing and tourism (Storrs & Julien 1996). Despite quarantining the Magela floodplain and undertaking other efforts to prevent the weed spreading in the park, a new infestation was found in 1990 in Nourlangie Creek, a tributary of the South Alligator River. This infestation, though downstream, is very close to the major tourist destination of Yellow Waters (Storrs & Julien 1996). Previously in 1989 an infestation was also found in a tributary of the East Alligator River, nearby in Arnhem Land (C.M. Finlayson pers comm).

The apparent lack of control in some years by the weevil was unusual and prompted ANPWS (now Parks Australia North) to contract CSIRO to undertake a 3 year research project, starting in July 1991. The project was designed to monitor the environment, the weevil and the weed to determine factors limiting control and to look at ways of improving control (Julien & Storrs 1993, 1996, Storrs & Julien 1996).

4 Results of the CSIRO salvinia project

The weevil population was found to be well distributed throughout the study area; thus there was no need to make any further large-scale introductions. However, the weevil population and associated plant damage were observed to have annual cycles. The numbers of weevils increased dramatically during the mid Dry season (May to September), and then rapidly declined shortly afterwards in the late Dry to early Wet season (October to January). During the time of this study the trend was consistent from billabong to billabong although it was not synchronous between billabongs or within billabongs (Storrs & Julien 1996).

The study examined factors such as the effects of high temperature, nutrient availability, changes in water quality and predators and pathogens that may have caused or influenced the decline in weevil numbers (Julien & Storrs 1993). Experiments showed that high temperature had no significant effect on adult weevil survival, fecundity or on egg laying and hatching. Salvinia nutrient analysis suggested that changes in the populations of the weevil were not limited by nutrient availability. Preliminary assessments of water characteristics indicated that when water quality changes occurred, they did not affect all billabongs, whereas weevil populations built up and declined in all billabongs about the same time. Assessments of weevil predators showed that although they were present, numbers were insufficient to contribute to the dramatic population declines observed. No diseases of the weevil were found (Julien & Storrs 1993).

It was concluded that the decline in weevil numbers was due to the severe damage that the weevils did to the weed. The rapidly increasing weevil populations destroyed the quality of the weed to the point in the late Dry season when there were no growing tips left (the food of adult weevils) and all rhizomes were hollowed-out (the food of the weevil larvae). This resulted in very high weevil mortality rates which reduced the populations to low levels (Julien & Storrs 1993).

Wet seasons in the region can be extremely variable and this variability appears to significantly affect the dynamics of biological control of salvinia. The onset of the monsoon can occur over an extended period, or not at all. As well as the timing of the Wet season floods varying, the timing of the weevil population build-up and decline also varies from year to year. The difference in salvinia biomass accumulation from year to year seems to be linked to the timing of crash of the weevil population, coupled with the timing and volume of flooding. The results showed that, in some years little salvinia growth occurred, restricted to a large extent by the action of the weevil whereas, in other years, salvinia biomass increased rapidly, often resulting in complete cover of the billabongs (Storrs & Julien 1996).

Rains of the early Wet season and the initial flooding during each Wet season provides an influx of nutrients to the billabongs and it is hypothesised that there is a consequent high growth potential of salvinia (Storrs & Julien 1996). In a 'good' Wet season floods arrive early and the follow-up flood waters dilute the system, decreasing nutrient levels and thus reducing salvinia's growth potential. In a 'poor' Wet season, major floods are slow to arrive allowing 'a soup' of relatively nutrient rich waters to remain in the billabongs for some time with a consequent high growth potential for salvinia. If weevil numbers are low at this time this growth potential is achieved. In a 'poor' Wet season the nutrient influx can be intensified by 'fish kills'. The fish kill can take place over a number of days and involve thousands of fish within a billabong. The dead fish quickly decompose releasing nutrients into the system which can assist the growth of salvinia (Storrs & Julien 1996).

During the time of the study, when major floods arrived early in the Wet season the flushing effect, coupled with the fact that weevils had not yet declined to low numbers, meant that the weevils were able to restrict the lower growth potential of the weed. Both populations of the weed and the weevil increased, but the relative abundance was such that the weevil suppressed growth rates, restricted biomass increase and the level of cover by the weed (Storrs & Julien 1996).

Conversely, when floods arrived late, nutrients brought by initial rains stimulated rapid growth in salvinia which continued for some time before any flushing took place. This, coupled with the fact that weevil numbers were extremely low meant that the salvinia increased without restriction. Although weevil numbers started to increase they could not prevent the exponential increase in salvinia biomass. The increase in salvinia peaked, on average, in September. By this time, or shortly afterwards, weevil populations had built up sufficiently to sink the mats, or at least, greatly reduce their biomass. Remnant, heavily-damaged mats were usually flushed out by flood waters during the next Wet season. Occasionally, however, a second or even third poor Wet season occurs and damaged mats are not flushed. Each new season's growth of salvinia and other vegetation supported on the mats, adds to the already high plant biomass and forms a thick sudd. This habitat is much less suitable to the weevil, much less likely to sink and more difficult for average flood waters to remove. Such sudds developed in the Magela system in 1987 and covered billabongs until 1989 when floods removed them during the Wet season of 1989/90 (Storrs & Julien 1996).

5 The prospects for improving control

It must be emphasised that biological control of salvinia is a cyclical process. Further, the CSIRO study showed that there was no benefit to be gained by continuous and repeated introductions of the weevils into areas of the Magela floodplain where the weevil was already established. Even in poor Wet seasons the numbers of weevils released were insufficient to modify the level or timing of damage compared with that caused by existing field populations (Julien & Storrs 1993).

With a better understanding of the relationship between salvinia and the weevil in Kakadu National Park, the situation of inadequate control in late arriving, poor Wet seasons could perhaps be improved by integrating biological and chemical control techniques (Julien & Storrs 1996, Storrs & Julien 1996).

The chemical AF100 had been recommended for use on salvinia in Kakadu National Park by the Commonwealth Environmental Protection Authority. AF100 is a formulation of kerosene and a surfactant called Kemmat which has the effect of breaking the surface tension of the water allowing the weed to sink and drown (Diatloff 1979). Studies conducted on the ecotoxicology of the herbicide spray in Kakadu National Park found it to be relatively benign (Finlayson et al 1994).

During the CSIRO study an integrated trial was conducted that indicated that salvinia cover could indeed be further reduced by spray application of the herbicide. The timing of application was found to be important if resources were to be conserved and minimum herbicide used (Julien & Storrs 1996, Storrs & Julien 1996). The best time for application was found to be immediately after the peak water flow in the Wet season. Application at this time was shown to significantly reduce the recovery rate of salvinia during the following early Dry season and occurred after the biological control agent had reduced the salvinia biomass to its lowest levels. In addition, Wet season water flow through billabongs reduced the toxicological effects of the herbicide (Julien & Storrs 1996, Storrs & Julien 1996).

It is not desirable to introduce large-scale use of chemicals in a World Heritage Park. Rather the situation calls for a light-handed approach; for instance, there was little need for chemical intervention in the Magela system over the years 1992–1997.

6 Conclusion

Salvinia is present in the Kakadu region and is very unlikely to be eradicated. People must learn to live with some level of salvinia. The weevil is certainly contributing to the control of salvinia in Kakadu National Park by restricting growth rates and biomass accumulation, although this occurs in a cyclic manner. This is classical biological control at work.

The outcome of the CSIRO project was to develop a management strategy that would permit the biological control agent to work to its best effect but, when necessary, use herbicides to prevent salvinia biomass accumulation and cover on billabongs. Although we now know a lot more about the dynamics of the weed and weevil populations, a three year study of such a complex and dynamic biological system is a very short time and further data are essential. As further knowledge is gained from monitoring and spraying operations the management strategy can be further refined.

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Fire management and research in Kakadu

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1 Introduction

Fire is one of our major management issues in Kakadu National Park, indeed as it is throughout the Wet-Dry tropics. It is of equal management importance with weeds and feral animals, and of course all three factors interact.

It's important to realise that fire has been part of the landscape for a long, long time. Even before the Aboriginal people arrived, fire was caused by lightning, although the climate and vegetation would have been very different from now. Certainly Aboriginal people have been burning the country for a long time and the vegetation is, on the whole, adapted to fire. The country is burnt much more regularly than in southern Australia and the fire ecology of the monsoonal tropics very different to that of southern Australia. We have regular fires through the savannas which are typically cool compared with those in the southern eucalypt forests. They generally don't get up into the canopy, but tend just to burn the grassy understorey.

The perception of visitors to the Park is that we are burning too much, and that comes from the southern perception of fire and the devastation of events such as Ash Wednesday. It is simply not like that here in Kakadu. It is inevitable that the country will burn every few years or more often, even every year if we don't manage fire properly. Hence our management strategy is to light fires; that's our major tool for fire management.

2 Aboriginal use of fire

The Aboriginal people use fire for hunting purposes, to drive game; for green pick, to encourage that regrowth to bring game into the country; and to clear the country to make travelling easier. In fact they regard burning as 'cleaning up the country'; the country is often regarded as unclean if it is not burnt, so it is part of their culture to burn. There are also spiritual reasons for burning or not burning in certain places. Certainly in some areas of Kakadu National Park, Aboriginal people used to burn to protect particular resources, for example monsoon rain forests which are rich in foods like yams. They would back-burn away from the forest in some parts, although we don't know if that happened in all places. The effect of Aboriginal burning is to produce a mosaic of burnt and unburnt patches early in the year, which creates a diversity of habitat for game and reduces the late Dry season fires which are typically much more intense and widespread if they are not controlled by mosaic burning. It creates fire breaks.

3 Recent fire regimes

During this century, fire regimes have changed considerably from the typical Aboriginal fire regime. In Kakadu this happened largely because the country was de-populated early in the 1900s. There was a drastic reduction in the Aboriginal population, mainly through the introduction of diseases by settlers, but also through people moving off their country to towns and settlements.

So, there were simply not enough people there to continue burning the country. Then pastoralism began in the area and the pastoral managers had different reasons to burn. The country was typically burnt later on in the year.

The population of Aboriginal people has grown since Kakadu National Park was declared, but not to anywhere near pre-European settlement levels. Burning patterns today are not exactly the same as pre-European settlement ones, and burning is now more concentrated around settlements and roads, reflecting changes in movement patterns and methods. This is reasonable, as Aboriginal culture has always been dynamic, never static, and these changes have been adopted into their culture.

4 Fire management

As outlined in the Kakadu National Park Plan of Management, fire management objectives in the Park are:

- To protect life and property within and adjacent to the Park
- To maintain, as far as practicable, traditional *Bininj* burning regimes within the Park (*Bininj* meaning Aboriginal people)
- To maintain biodiversity.

There is also an aim to promote research into the fire sensitivity of environments, which will enable the identification and protection of sensitive environments.

The challenges to us in our management program are:

- How do we go about maintaining traditional burning patterns and maintenance of biodiversity?
- What is the appropriate regime in each different habitat within the Park that willmaintain biodiversity?
- How do we repair the damage from years of inappropriate fire regimes?

The damage from inappropriate fire regimes in the past is reflected in a great proliferation of speargrass, the native *Sorghum spp.* Speargrass is an annual grass and a fire weed which under prolonged, regular, late-Dry season burning has spread considerably further in the Park – in fact across the Top End – than it would naturally occur. It is a self-perpetuating process because it is very much promoted by fire, and in turn it promotes fire by increasing the fuel load. All the seeds are in the seed bank before it burns, waiting for next year's rains to come before they germinate.

So having realised the predominance of late season fires from our own observations and also from several satellite imagery studies that were done during the 1980's, the Park decided to adopt a much more strategic and systematic approach to fire management. This largely involves aerial ignition using helicopters, together with strategic burning on the ground, for example around the Jabiru township and infrastructure, fences, Park boundaries, and around sensitive habitats like small patches of monsoon vine forests which are not as resistant to fire as the savanna vegetation. This is the only way that we can simulate traditional burning patterns because, even with all the Park staff and a few hundred Aboriginal residents, we can't do it the way it was done. We simply do not have the same number of people covering the same amount of ground that there were a hundred years ago. We cannot be as accurate when lighting fires from helicopter, but it's the best we can do at the moment. Using this technology we can do early mosaic pattern burning and, hopefully, we will ultimately achieve the same effect as was achieved before by many Aboriginal people travelling over the country.

4.1 Wet season burning

We also have a program of Wet season burning. The aim is to save some country from being burnt during the Dry season, which is not always easy, especially if it is near roads or towns. On dry days in the Wet season the previous year's dead speargrass crop can be burnt, which will kill the young new season's speargrass. As speargrass seeds only last for one year in the soil, you can actually knock out nearly all of it out with a good Wet season burn. In practice, however, the danger is that someone will light up a large patch late in the season and instead of getting a nice Wet season burn, you get another destructive late fire. This has happened often but there has still been considerable success in reducing speargrass throughout the Park.

While overall we have achieved considerable success in changing the fire regime from predominantly large, late fires, to a patchwork of early small fires, we have some way to go with a lot of questions still to be answered. We still have a lot to learn about the effects of different fire regimes on vegetation and fauna, and especially about fire and weed interactions. For example, in the southern part of the Park where we have been doing Wet season burns, the introduced weed *Crotalaria goreensis* seems to love it. It comes up in huge areas and is spreading without our help so it is going to be a major problem there.

We also have more to learn about protecting the relatively fire-sensitive habitats. In general we believe that the fire frequency is still too high, especially in savanna woodlands and forests and the sandstone country.

4.2 Fire-sensitive habitats

In fire research and management, we need to look at the three broad habitat types in the Park:

- lowland open forests and woodlands (the savannas)
- floodplains
- sandstone plateau and escarpment

Obviously there is diversity within those types, but they are the broad categories, each with their own fire and management problems. Generally, the most fire-sensitive communities are the monsoon rainforests, the *Callitris* pine communities and the sandstone heaths. They are all fire-tolerant to a certain extent, but are susceptible to changed regimes. The *Callitris* pine is particularly fire-sensitive and many are being killed by hot fires, and are not regenerating, right across the top half of Australia, from Western Australia to Cape York. The sandstone heath communities are adapted to particular fire regimes, but high frequency, intense, late season fires are very destructive to these habitats. The impacts of hot fires on monsoon forests, which occur in isolated pockets within wetland, lowland and sandstone habitats, range from margin erosion to complete destruction.

4.3 Burning the floodplains

The floodplains are different to the other two broad habitat types in that often you can't burn early and until a few years ago they were covered with buffalos. It was a completely different system then to what we have now as there simply wasn't the huge biomass of grasses and sedges present. Also the floodplains have particularly drastic weed problems, for example Para grass (*Brachiaria mutica*) in Kakadu and *Mimosa pigra* outside the Park. Grassy weeds such as Para grass are a problem and obviously affect the fire ecology of floodplains. There has not been a lot of research done on floodplain burning and it has been identified as a priority for future research in the Park. Sue Roberts (Braithewaite & Roberts 1995) has studied floodplain burning patterns, and Diane and Kate Lucas (1993) and Jeremy Russell-Smith et al (1997a) have done a lot of work with traditional owners which probably gives us the best indications for fire management of the wetland areas. Floodplain burning is a fine art and the best practitioners in Kakadu are the Aboriginal custodians.

Aboriginal people practise progressive burning, setting fire to the flooplains as they become dry enough to burn. This reduces species like *Hymenachne acutigluma,* which will otherwise tend to form monocultures and exclude other species, for example lilies, and *Eleocharis* bulbs which are an important resource for Aboriginal people and magpie geese. Research carried out by Peter Whitehead in the Mary River region has shown that burning helps to increase species diversity on the floodplains (Whitehead & McGuffog 1997).

Burning also reduces the humic build-up from the grass cover, which if allowed to build up can cause very slow-burning but high intensity fires in the humic layer. Such fires are unstoppable and will burn entire floodplains, killing turtles in the mud if they are not yet buried deep enough. Sometimes turtles cannot even bury down into the mud if there is a thick humic layer, and instead bury into the grass layer, where they are burnt. Out at Oenpelli there is a lot of Para grass on the floodplain, and Jacob Nayinggul told me that they are digging up the turtles already cooked!

The same hot fires also slice huge Melaleuca trees off at the base, killing them. Some believe this is a problem, but others argue that losing the Melaleuca trees is a natural course of events following removal of the buffalos. They argue that the Melaleuca stands are there as a result of the huge numbers of buffalos present in the past. I don't think that these discussions have appeared in the literature yet. We also face serious problems with hot fires damaging the pockets of monsoon forest that occur on or adjacent to the floodplains. Again, these problems are compounded by the presence of para grass.

In the past the floodplains were a major focus of activity and quite heavily populated in the dry season, with people moving around and burning expertly as they went. The nature of progressive burning of the floodplains means that it is labour intensive, and now the population is simply not there in most areas. The major challenge for the park managers is to maintain fire regimes that protect biodiversity and cultural resources with a very limited labour force. We do not possess technology that can replace the presence of people on the floodplains.

5 Fire research

5.1 Munmarlary fire experiment

The lowland savannas are the best studied of the vegetation systems to date, and several major research programs have been conducted in the Park. The earliest was the Munmarlary fire plot experiment, begun in 1972, in which a series of one hectare blocks were treated with four different fire regimes. This experiment is still running now, twenty five years later, except that all but one of the plots were unintentionally burnt this year. It will be interesting to find out where that fire came from – no one is confessing to it! We simply couldn't get any equipment in there before it became accessible after the end of the Wet to create fire breaks or do back-burning in time to stop the plots being burnt.

The Munmarlary experiment results have been written up by Hoare et al (1980) and David Bowman et al (1988), and now Jeremy Russell-Smith is in the process of doing a final analysis and documenting the twenty five year results. Although the experiment was heavily criticised by Mark Lonsdale and Dick Braithewaite (1991) on the basis of its design and analysis, it will prove to be a very useful exercise. Bowman et al (1988) concluded from the 13 year results that soil factors were more important than fire in determining vegetation patterns. The twenty-five year results will be very interesting indeed.

Animal studies done by John Woinarski on birds (Woinarski 1990) and Alan Anderson on ants (Anderson 1991) at Munmarlary, and by Dick Braithewaite on lizards (Braithewaite 1987) elsewhere in Kakadu, clearly show that different animal species have different preferences regarding burning regimes. They recolonise areas at different rates following burning, and cope with different burning intensities. The upshot of that for management is that not only should we aim for a mosaic of burnt and unburnt patches, but we must really aim for a mosaic of patches with different fire histories. Some animals prefer freshly burnt country, others 1–3 years since burning, and others unburnt country. Only a few species prefer completely unburnt country, but there are many species which rely on relatively fire-sensitive habitats like monsoon vine forests.

5.2 Kapalga fire experiment

A major fire experiment on savannas was also conducted by CSIRO at Kapalga. This was a landscape-scale fire experiment conducted for 5 years (1990–1994). Kapalga is a large area between the West Alligator River, South Alligator River, the Arnhem Highway and the coast, and it was divided into twelve compartments, each being a single catchment of 15–20 km^2 in area. Four fire regimes were chosen, each with two replicates; early-burn, late-burn, progressive-burn (burning down the slope as the vegetation dries out) and natural (protecting it from other fires but allowing nature to take its course). It was a multi-disciplinary study with six core projects; nutrients and atmospheric chemistry, temporary stream vegetation and insects, small mammals and vertebrate predators.

Most results are yet to be published from that experiment, although Michael Douglas (Douglas & Lake 1996) provides an insight into temporary stream flora and fauna responses under different fire regimes. Results for several research areas were presented at the recent Bushfires '97 conference (McKaige et al 1997). Most of these researchers, except Alan Anderson, prescribed early burning, as the Park is now doing, as the best management option for maintaining biodiversity (Anderson 1997; Corbett et al 1997; Griffiths 1997; Williams 1997).

5.3 Wet season burning research

Wet season burning is an important tool for reducing speargrass, and some research has concentrated on this aspect of fire management. Williams and Lane concluded that late December fires give the best result, assuming that it has started to rain (Williams & Lane 1996, Lane & Williams 1997). It means that we should burn in the early Wet season, before the rains really set in. They found an increased abundance of forbs after 1996–97 Wet season burning, a change in the species competition and reduced fuel loads in the following year. Kym Brennan (1997) found an overall reduction in biomass of the understorey layer, but an explosion in the biomass of an array of relatively diminutive grasses and herbs. Preliminary data from the photo monitoring plots (see below) are showing a significant increase in species diversity in sandstone habitats following Wet season burning. Joye Maddison (unpublished results) has been monitoring spear grass plots and has found that the sorghum takes approximately 5 years to recover, even in a small plot close to neighbouring areas which are a ready source of seed.

5.4 Remote sensing

5.4.1 LandSat MSS

There is currently a major project underway to construct a fire history for Kakadu National Park, using LandSat Multi-Spectral Scanner (MSS) imagery, from 1980 to the present. This involves obtaining at least three coverages for every Dry season. From 1980–90 these images were mapped manually, but since 1991 they have been mapped using interactive digital techniques. The results show that since 1980, on average, 46% of the lowlands, 28% of the floodplains and 28% of the sandstone country have been burnt annually. There has been a marked change since the mid-1980s from large, late Dry season fires to a lot of small, early Dry season fires. There has also been a marked increase in floodplain burning in the few years since the removal of buffalo. Most of the sandstone country is still being burnt in the late Dry season.

Ground-truthing is important in this exercise. This is done by helicopter, flying transects and taking GPS readings, recording points as burnt or unburnt every thirty seconds in random transects throughout the Park. Ground-truthing is done a few days before the satellite overpass. All the data is stored in the Parks Australia North GIS system, ERMS, which incorporates other GIS coverages such as boundaries and landscape units, vegetation, hydrology and topology. Derived coverages include proximity analysis and frequency of burning. From the ground-truthing, we know that the degree of accuracy in the interpretation of the imagery is over 80%.

Analysis of the GIS data (Russell-Smith et al 1997b) show that the lowland savanna sites are being burnt on average 3 out of every 5 years, which is significant. The majority of sandstone sites were burnt on average between 0–4 times over the past 15 years, and floodplains between 0–3 times. The medium size of continuously burnt areas has been declining steadily, from over 300 hectares in the early 1980s, to about 60 hectares now, largely because the fires are cooler. As burning is done in the cool part of the year the fires tend to extinguish at night.

There are a few problems with LandSat MSS imagery. For example, cloud cover during the Wet season means that Wet season burning can't be recorded and small burns are often missed. There are also positional errors of up to 300 metres which mean that you can't follow the fire history of individual pixels or a single point.

5.4.2 NOAA AVHRR

We are also starting to use NOAA AVHRR imagery which has several advantages; it is free and is flown daily. Unfortunately it has a very low resolution (1 km^2 pixels), so it is without the detail of LandSat MSS imagery. However it has proven to be very useful, having great potential for day to day management of fires.

5.5 Photo monitoring plots

In conjunction with the fire history and fire scar mapping projects, photo monitoring plots have been established throughout Kakadu, including the wetlands (Ryan & Russell-Smith

1995). The plots are 40 by 20 metres with a fixed point for taking photographs. All the trees are tagged and an inventory made of all trees and shrubs. They are divided into size classes, counted, and ground cover is estimated in a series of 1 m^2 quadrats. The site is well described. This study is set up to continue for at least 90 years, the life of the Park lease. It allows us to monitor the responses of a lot of single sites with very accurately known fire histories. The sites are visited twice a year, photographed, and ground truthed for burning. It involves many Kakadu staff, giving it the advantage of staff ownership of and involvement in the research, and the consequent potential for direct application of the results to management.

5.6 Sandstone habitat research

Similar to the photo monitoring plots are plots that have been established in sandstone habitat (Russell-Smith et al submitted) in the three fire-sensitive communities occurring there; the monsoon forests which are dominated by *Allosyncarpia*, the *Callitris* pine stands, and the sandstone heath vegetation. The big problem with the sandstone areas of Kakadu is that all the western Arnhem Land area across the eastern boundary of the Park is de-populated and is not being managed at all. As a result, huge fires, often with a 100 km front, sweep across the boundary into Kakadu, driven by the south-west winds. One year a fire was traced back to the Ramingining dump, 300 km to the east. This is a very serious management problem because the sandstone communities are species rich with a very high level of endemism, much higher than in any of the other habitats in Kakadu.

The *Allosyncarpia* forests are currently being eroded at the margins and broken up by hot fires. The heath communities are also at risk. 54% of the sandstone heath plants are obligate seeders and won't re-sprout after they are burnt. They are killed by fire and depend on reproduction from seed, taking up to 5 years or more to reach maturity. *Callitris* pines take much longer to mature, and that means if we have fires at a frequency greater than 5 years, we start to lose those species. Fire-tolerant species such as speargrass then invade the sandstone heaths. It is vital that we gain an understanding of their fire ecology and develop methods to stop large fires coming into the sandstone, both from within and outside the Park.

6 Conclusion

Burning patterns have changed since Europeans arrived and there is a legacy of inappropriate fire regimes for the conservation of biodiversity. The Aboriginal traditional fire regimes were obviously appropriate because the biodiversity is there. The fire regime changes included more frequent fires later in the Dry season; larger, hotter, and more destructive. Our aim in adopting or simulating the Aboriginal burning patterns is to break the country up by lighting early Dry season fires and creating a mosaic of small patches with differing fire histories. In this way large, destructive fires are avoided because the breaks are already in place when the inevitable late fires occur. While the Aboriginal custodians are well aware of this, and use their knowledge to manipulate the system with great skill, western scientific research results also indicate that these patterns are most beneficial for the maintenance of biodiversity,

In the sandstone, where the highest levels of biodiversity and endemism are, the most serious fire management problem is caused by vast destructive fires sweeping across the boundary from outside the Park. In the wetlands, which are extremely important both culturally and as habitat for wildfowl and other species, the major research and management hurdles revolve around understanding the traditional burning patterns and achieving the same results with vastly reduced numbers of people involved.

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Traditional Aboriginal use of fire in wetlands

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1 A description of traditional burning

In the mid-Dry season each year, people will start to burn from the open woodland and work down towards the wetland system. The way Aboriginal people burn is by following the weather; the season's climate tells them when it is the right time to burn. They usually tell when the last storms in the Wet season occur, which are called 'knock em down storms'. The storms bring the wind which knocks the spear grass, twisting and turning it, so the spear grass falls flat. When Aboriginal people see that, they get ready for the burning season. That's when the early burn usually starts, first burning the woodland country, what they call the high land.

People then start watching the storms. Once the storms have finished, they know the next thing to come is the cold weather season, and that will bring the moisture out and form dew on the grass. People will start burning the higher, open woodland country first. They start by doing a patch burn, or what we call a 'test burn'. What people would usually do is burn a little bit of the country to see how the grass would burn. If it burns a fair distance, then no worries, it's good, they will come back the next day and keep burning it. So people will start burning the higher ground and work their way towards the wetland system, because the wetland and the flood plain areas are the last to be burnt.

People usually burn the country in the mornings. The reason why they burn in the morning is because the dew causes the fire to burn slowly and die out. They sometimes burn in the evening, because they know that the fire will burn during the evening with a slow wind behind it and die out during the night because of the dew.

Something people say is not to burn when there are big winds, because if you do, the place will be damaged. The traditional knowledge is that once you are burning a country you have to burn behind the wind, so the wind will push the fire forward. Those are the sort of things that traditional people learnt from their ancestors.

You have to look at which way the wind is blowing. We have different patterns of wind; slower wind, fast wind and light wind.

Fast wind carries the fire really fast and everything gets burnt. Slow wind will cause the fire to burn slowly. People start to gradually burn in late afternoon, morning and sometimes at night; they burn when it is much cooler. Then once you get down towards the floodplains, that's where you start looking at your food resources in that area, because if you burn too early on the floodplain, the freshwater long neck turtle would get burnt. Turtles don't bury themselves very deep during that early period in the Wet season. You have to wait until late in the Dry season when the water table has started going down and the turtle bury themselves deeper. If you burn too early you will burn the freshwater turtle. The only way of finding that out, in the traditional way, is to go and look for the turtle yourself to find out if it is ready to burn. If you find some turtles still shallow, you know it is not the right time to burn.

The only knowledge people have is 'feel'; feel is the most important thing in the Aboriginal societies. When people burn they follow the 'feel system', and you burn from the woodland country following down towards the floodplain. Once you get to the floodplain, the first thing you check is your feel. If you feel it's too green, you check the animals that live there and if things are too green, don't burn. The main thing is checking the freshwater turtle, it is the most important thing that people check. Once the water table goes down the turtle buries itself deeper, then they can burn the country.

The other thing that the old traditional people say is that burning the floodplain is good because you burn most of the grass on the floodplain, and the next coming year it will make more grass for the magpie geese to lay their eggs. It cleans the old area. They usually burn around the jungle forest area, but they usually burn that early to protect the food, the yam and all.that sort of stuff. If you burn late, the fire goes inside the jungle and damages all the food sources there, it is all gone.

So I think I'll leave it at that, and if anybody has any questions, I am happy to answer them.

2 Questions

Question: Could you give the reasons why traditional burning is done by Aboriginal people?

Why do we burn the country? The country tells us when to burn. If we don't burn the country, the country is not going to look after us; that's the old saying that Aboriginal people always have in their mind. So the reasons why we burn the country are:

- For hunting reasons
- To clear the vegetation for people to walk and hunt
- People feel good burning the country to make everything come alive. The animals come back; the wallabies, kangaroos, white cockatoos and black cockatoos come back and feed on the spear grass. The white and the black cockatoos come and feed on the burnt spear grass seeds; they are the main food source for the white and black cockatoo. Other little animals come and feed on things too. If you don't burn, going back to the food chains, all the other animals wear out that access to feed on things.

Question: Do you take the cultural sites, the sites of historical significance, into consideration when you burn?

Only the right people can go to burn there, those who know that country and know that site there. Some important places do get burnt.

Question: Is there any cultural significance in burning?

There are a lot of different burning techniques. You can burn along the country and if a fire is used for smoking animals, they are the sort of thing that continue on. With cultural reasons, people sort of follow on from their ancestors, back towards Dreamtime, so fire is the main important thing to Aboriginal people today and they see it as not only burning the country. Fire is used in other techniques like when a relative or a person passes away, you do a smoking ceremony. You smoke their vehicle, their house, the food and then you have to smoke the land. These sort of things are how it ties into a big picture.

Question: One of the biggest problems we find when we burn early in the year is that it's obviously easier to burn off all our planned areas, or even burn in sequence down the drainage lines, but the creek lines don't really dry out until later in the year and so they are really vulnerable to impact from late season fires. Do people talk to you about how things happened in the old days with the problem of drainage lines burning later in the year?

No. I mainly refer back to Arnhem Land, because that's where most of the people hunt and gather foods, more so than in Kakadu. They hunt where the river system or the creek system is, and every time people hunt there they usually burn. You get a broader knowledge of your country, where every little thing is. You know if there is a creek there, you have to burn all that to preserve it and that's what is happening in Arnhem Land. There are a lot of people that go hunting and they burn their clan boundary area, because if they don't burn it, people from the other clan boundary will burn their area and the fire will come over the boundary.

But there is not much activity here in Kakadu. It is much bigger, and harder trying to get to all the creek lines. Traditionally, people would burn for various reasons, like when hunting for yams and other food sources, or maybe when travelling to other places they would burn there.

Question: Does Arnhem Land get burnt much traditionally?

I don't know the areas east and west from here, but I think when there were more Aboriginal people living there, they used to burn traditionally. Most traditional burning occurs in Arnhem Land, that's where a lot of people burn traditionally.

Question: With the fire regime in Arnhem Land, satellite images we're getting suggest there are some large, intense fires coming through late in the Dry season. Is that simply because there's not many people there now, or is there some other reason for those late fires?

The spear grass is different in Arnhem Land than here. In Kakadu the spear grass is thicker, in Arnhem Land you have thinner spear grass; they are different. When you burn the thinner spear grass it doesn't do much damage to the country, that's what I have found in my work, looking at things in Arnhem Land and looking at things in Kakadu. The thinner spear grass in Arnhem Land doesn't burn as hot as in Kakadu, and you haven't got many people staying in Arnhem Land as people travel backwards and forwards. Also they haven't got the machinery and things we have got in Kakadu. Here we have got a helicopter doing the burning, people doing controlled burning, and all this sort of thing doesn't happen in Arnhem Land.

Question: Do they have the same ideas with burning early in the year as here in Kakadu?

No, it's different there. They have different seasons and they follow different things there than what it is here in Kakadu. In Kakadu Aboriginal people follow six seasons, but in Arnhem Land they only have four seasons. In those four seasons, different clan groupings and different areas have different knowledge of how to burn and at different times of the year, so some people will burn earlier, some people will wait and burn a bit later.

Question: So maybe they think because there is not so much fuel, it's not so important to burn early in the year and they don't have to worry so much?

Yes.

Question: Is Wet season burning a traditional method?

No it wasn't, not here in Kakadu. The work I am doing is looking at that. Some traditional people say the Wet season burn is not our traditional burn, and they are pretty upset about it.

They say that if you want to follow the traditional burning you have to follow the way the season indicates to you.

Question: Although Wet season burning is not traditional, some Parks staff want to encourage Wet season burning to break up the big areas of spear grass (Sorghum intrans), because it has only one year's worth of seed and if you burn the spear grass before it sets seed then it doesn't come back for the next few years. You are saying the black and white cockatoo in particular come onto the spear grass, so do you think that it's a good thing to promote Wet season burning?

In my experience, if all speargrass went, when the Dry season comes and we go to hunt the animals, they are not going to be there because there is not any regrowth. However, Wet season burning is good in a way. It does act as a fire break in some areas I have seen, and then if we get a late fire go through that area, the burn would stop where the Wet season burn was done. So the Wet season burn does act as a good fire break for when you get late fires coming through.

It goes back to the traditional side of things, people get upset about it because it makes their hunting pattern much different.

Question: With monsoon forest, the problem seems to be that, over a number of years, the fuel inside the monsoon forest keeps on building up and you end up with early fires going through. One way or another the fire gets in there and seeps through all the litter layers. Is that something that just happens occasionally and you can't do much about?

That is something that does happen occasionally, but going back, it doesn't happen much in Kakadu. However people in Arnhem Land usually go and hunt in the monsoon forest area. They usually burn there earlier while they are there hunting, digging for yams, because they know that there is not much wind in that area and the fire will burn really close, creeps in. So I have seen a lot of people do that in Arnhem Land, but it isn't done much around this area.

Question: Probably a good example is the monsoon forest behind the buildings at South Alligator Ranger Station. Fire had been kept out of there for a number of years, but when it did get in there it got into the litter layers and just kept going and going. Everyday we tried to put it out but it flared up again. I'm wondering, as far as long term management of monsoon forest goes, perhaps you have to protect the forest as much as you can and accept that once every 10 years or so, fire is going to get in there?

At this stage they are starting to look at most of the facts around the monsoon forest and they are working out a strategy of how to preserve it, to stop late fires getting into there. You have to burn around early and do a firebreak earlier. It is a bit hard because in Kakadu you have got so many rainforests, people are not going to go to every different place, but there is a concern about it and at several meetings people have raised that concern, so they are looking at a way to improve it.

Question: What about paperbark swamps? Do you see them as being like monsoon forests that shouldn't be burnt? Are paperbark swamps an area that gets burnt traditionally?

There is a good story about paperbark. If you burn the paperbark tree earlier in the year it doesn't get damaged. Because the tree holds water inside, it's one of our main trees; we know we can find water inside a paperbark tree. But if you burn late, the water in the paperbark tree will be drained out and it will kill it. That's why most of the people burn that area early because they know that it is water you can survive on late in the Dry season if you are travelling. For paperbarks, an early burn is OK, but a late burn is not. I remember one area in

Kakadu that had a late burn, and a really big paperbark tree and a lot of other big trees got killed.

Question: Since the buffalo have been taken off the floodplains, the vegetation on the floodplain has changed and so has the fire regime. Also there is Para grass on the floodplain now. What are your comments on that?

The removal of buffalos has caused a fair bit of change. I remember when I was here in 1979, most of the floodplain area didn't used to get burnt because of the numbers of buffalos eating down the grass. Now that the buffalos have gone there is more fuel there and you really have to concentrate on how to control fire on the floodplains because it will burn hotter than it used to before. That's the sort of thing that we noticed in Kakadu; when there is more fuel on the floodplain it burns much hotter for the animals, so you have to get in virtually when the water starts going down and burn slowly.

Question: So it actually takes more fire management now to avoid those hot fires?

Yes, management of burning has increased.

Question: What do Aboriginal people think about the removal of the buffalo? Do people want them back?

Well a lot of people are saying that they wouldn't mind the buffalo to come back, but then you get other people looking at what damage was done and how the floodplains are totally different now. Those people would prefer that the buffalo come back but in a controlled number, for a controlled measurement of impact.

Question: Do you know or can anyone else remember before the buffalo were even here, what the fires were like around then and if the Para grass in particular burnt hotter than any other grasses?

No, you would have to talk to some of the older people who used to shoot buffalo. They might have more experience on that.

Question: Is the problem with the floodplain burns being hotter now actually that it messes up collecting turtles and stuff? Is that the real problem?

I remember once, a couple of years back, there was a big burn at Boggy Plain. There was a big burn on the floodplain edge and a couple of days later we went out there to have a look. You could see that there were thousands and thousands of turtles that got cooked, because the grass was too thick and people didn't manage it properly to get a good controlled burn on it.

But we found what usually happens with burning on the floodplain is that the fire travels underneath the grass like in a little tunnel, it doesn't travel on top. You can stand there and spray with your slip-on fire-fighting unit and you think the fire is out, but it is still burning underneath.

Question: You mentioned clearing the country for turtles and geese. What other food resources are you burning the floodplains for?

Referring to the floodplain area? Well, people say they burn there for the risk of snakes, that's one of the main things. People burn when they are travelling from one place to the other, making a much clearer access for walking. The reasons why people burn the floodplains are for turtle hunting, and making the grass much better for the magpie geese and crocodiles to lay their eggs the next year.

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Implementing the Ramsar Convention in Australia

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(Adapted from transcript)

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1 International Law

First of all I am going to give you a crash course on International Law. This normally takes a little longer than five minutes, but we'll see how we go. I'll start with some generic International Law issues, then we will examine the Ramsar Convention and its implementation in Australia.

Why do we have treaties? It could be as a response to specific issues or to develop relations and trade. We have treaties on the environment, trade, defence, aviation and communications. We often hear about international law, particularly environmental and human rights law, as being aspirational rather than something that can regulate our actions. Yet treaties are binding instruments only not quite in the same way as municipal or domestic law. This is because there is no direct supra-national enforcement. Breaches of international law can be addressed by the International Court of Justice (ICJ), but it is for nation states to accept its jurisdiction; it is not mandatory, unlike domestic legal systems. The findings of the court also are not enforceable, it is expected that States will accept and act on its findings in good faith.

The force of international law is really predicated on States wanting to be a member of the international community, a good international citizen. This will be prey to domestic political, social and economic situations. For example, Australia usually likes to be seen as a good international environment citizen, but our present Commonwealth Government's hostility towards binding reductions in greenhouse gas emissions under the Framework Convention on Climate Change were justified on account of Australia's 'national interest'.

International law can only be negotiated and enforced *by* states (in this context meaning national, not provincial governments) and not individuals or corporations, and only enforced *against* states. States must therefore act on behalf of injured individuals. Personality is required in international law. Australia has personality. This doesn't mean that it is witty at dinner parties, it means that it is recognised as a Party. It is necessary to have 'standing' in law at all levels. If you wish to go to court, you need to have standing before that court will recognise you to bring that case. Under International Law, to be heard, to negotiate and agree to a Treaty, you need to be a Nation State. Constituent States are not recognised (eg New South Wales, Queensland, Victoria).

> International Law is indifferent to the question of constitutional autonomy, or the division of powers, and regards persons exercising Governmental functions of any sort as agents of the international person.

That means the Commonwealth is vicariously liable in the international arena if the Australian states and territories do nasty things which breach Australia's international obligations.

The ICJ typically would not be the forum for, say, international environmental law. When it comes to enforcement of obligations under nature conservation treaties such as Ramsar, the emphasis is more on supervision through intergovernmental institutions – intergovernmental commissions, meetings of the parties (the Contracting States) – rather than state against state in a confrontational setting before the ICJ or arbitrators. These bodies fulfil a number of functions, not simple adjudication: developing the law, supervising its implementation, putting community pressure on individual states, resolving conflicts of interests. They gather information, receive reports on treaty implementation, act as a forum for reviewing the performance of states, and facilitate the negotiation of further measures. They become a forum for treaty compliance through discussion and negotiation, rather than by adjudication of questions of law. The aim is to secure compliance rather than to adjudicate on whether there has been a breach.

Where an issue is most likely to be arbitrated is with regard to conflicts over transboundary pollution or resource use, for example depletion of fish stocks. The crucial issue is whether the activities of one State affect another. This is less likely to be the case with regard to nature conservation unless a transboundary issue arises, such as deforestation in one Nation State affecting soil and water quality in a neighbouring State. We can see parallels with domestic environmental law where legal intervention into land use was developed in response to cases where pollution originating on one property caused damage to another.

Transboundary pollution was the subject matter of one of the foundation cases in international environmental law. In the Trail Smelter arbitration (1941 3 *R.I.A.A.* 1905) a tribunal awarded damages to the United States and prescribed a regime for controlling future emissions from a Canadian smelter which had caused air pollution damage. This case crystallised the international principle *sic utere tuo ut alienum non laedus* (so use your property as not to injure your neighbour's). This is what is known as customary international law which is developed by a combination of conduct – state practice – and the conviction that this conduct is motivated by a sense of legal obligation (*opinio juris*). It can be binding universally, regionally or between particular States and is generally a slow process.

Established principles of customary law include:

- the sovereign right of states to exploit resources within their territorial boundaries, but subject to:
- the responsibility of states 'to ensure that activities within their jurisdiction or control do not cause damage to the environment of other states or to areas beyond the limits of national jurisdiction', ie common property such as the high seas and airspace, and most of the living resources of these areas. (Principle 21 of the 1972 Stockholm Declaration on the Human Environment.)

These principles were reiterated in the 1992 Rio Declaration as well as in Article 3 of the Convention on Biological Diversity.

2 Ratifying a Treaty

In Australia we have a dual system. Not all countries have this, but it means that the executive council, that is, the Federal Cabinet, decide whether we are going to ratify a Treaty, but ratification does not mean that it has come into force in Australia. Unless we have domestic legislation which 'incorporates' the Treaty, it is not legally binding within Australia. While unincorporated treaty provisions cannot operate as a direct source of individual rights and obligations under municipal law, they may influence the common law (the law developed by decisions in courts rather than statute law which is developed by parliament). The High Court has emphasised the relevance of international law:

(a) to help resolve uncertainty or ambiguity in the common law

(b) to shed light upon the contemporary values of the Australian people

> The common law does not necessarily conform with international law, but international law is a legitimate and important influence on the development of the common law, especially when international law declares the existence of universal human rights.

Treaties may rely on the governments of each state/territory carrying out legislation, but it is overseen by the Commonwealth Government. It is possible to put a federal clause into a Treaty, stating that the Commonwealth Government agrees to attempt to put the treaty agreement into effect, but the implementation will be through the various jurisdictions of its constituent states, which may limit the treaty's effectiveness. Australia has done this once in relation to a Human Rights Treaty, the Convention of Elimination of Discrimination Against Women. The international community tends to regard a federal clause with contempt, viewing it as an attempt to avoid obligations by hiding behind its constituent jurisdictions. The Commonwealth Government says it will rely on state/territory legislation where the Treaty affects areas of their concern, however, it has stated that it 'does not favour including federal clauses in treaties and does not intend to instruct Australian delegations to seek to include them'.

3 Ramsar Convention

The Convention on Wetlands of International Importance Especially as Waterfowl Habitat was signed in 1971. It now has more than one hundred member States, known as Contracting Parties. Parties must designate at least one suitable site for inclusion in the List of Wetlands of International Importance for the Convention to come into force in that country. Unlike World Heritage Listing, the wetland site doesn't need to be checked to ensure that it is of outstanding cultural or natural significance, so occasionally a site is not quite up to scratch, or the boundaries are completely wrong, which has led to listings being modified at a later date to better reflect the significant area.

The first Ramsar site in the world was Cobourg Peninsula in the Northern Territory of Australia, inscribed in May 1974. There are now 49 designated Ramsar sites in Australia, including Kakadu National Park.

3.1 Selection criteria

A wetland should be considered internationally important if it meets one or more of these criteria:

1. *Criteria for representative or unique wetlands*

- it is a particularly good representative example of a natural or near-natural wetland, characteristic of the appropriate biogeographical region;
- it is a particularly good representative example of a natural or near-natural wetland, common to more than one biogeographical region;

- it is a particularly good representative example of a wetland which plays a substantial hydrological, biological or ecological role in the natural functioning of a major river basin or coastal system, especially where it is located in a trans-border position;
- it is an example of a specific type of wetland, rare or unusual in the appropriate biogeographical region.

2. *General criteria based on plants or animals*

- it supports an appreciable assemblage of rare, vulnerable or endangered species or subspecies of plant or animal, or an appreciable number of individuals of any one or more of these species;
- it is of special value for maintaining the genetic and ecological diversity of a region because of the quality and peculiarities of its flora and fauna;
- it is of special value as the habitat of plants or animals at a critical stage of their biological cycle;
- it is of special value for one or more endemic plant or animal species or communities.

3. *Specific criteria based on waterfowl*

- it regularly supports 20 000 waterfowl;
- it regularly supports substantial numbers of individuals from particular groups of waterfowl, indicative of wetland values, productivity or diversity;
- where data on populations are available, it regularly supports 1% of the individuals in a population of one species or subspecies of waterfowl.

4. *Specific criteria based on fish*

- it supports a significant proportion of indigenous fish subspecies, species or families, life-history stages, species interactions and/or populations that are representative of wetland benefits and/or values and thereby contributes to global biological diversity;
- it is an important source of food for fishes, spawning ground, nursery and/or migration path on which fish stocks, either within the wetland or elsewhere, depend.

This selection criteria can be applied to natural and artificial wetlands.

3.2 Obligations

The obligations of the Contracting Parties are as follows:

- listing and conservation of internationally significant wetlands as Ramsar sites
- commitment to conservation of listed wetlands and to manage all wetlands according to the principles of wise use
- the Contracting Parties shall formulate and implement their planning so as to promote the conservation of the wetlands included in the List, and as far as possible the wise use of wetlands in their territory.

The Ramsar Contracting Parties must conserve their listed wetlands as 'flagship' wetlands, but they are also supposed to use wise use principles for all their wetlands. This is obviously not adhered to as there are many examples of poor use of wetlands. The underlying issue here is the very nature of international law and treaties. In order to get many different people to agree, the law or treaty must be fairly general, and often will allow significant discretion. For example, Article 3(1) of the Convention provides:

The Contracting Parties shall formulate and implement their planning so as to promote the conservation of the wetlands included in the List, and *as far as possible* the wise use of wetlands in their territory. (Emphasis supplied.)

(A striking example of discretion in an international environmental treaty can be found in the Convention on Biological Diversity. Articles 5–20 inclusive require action by the Contracting States. Of those, ten Articles allow significant discretion in the interpretation of the obligations by inclusion of the term 'as far as possible and as appropriate'.)

By picking out wetlands for special attention, as distinct from the broader landscape in which they are located, the initial focus of Ramsar was a segmented one. That was exacerbated by the emphasis on listing 'flagship' wetlands. At the first meeting of the Contracting Parties, Recommendation 1.3 was adopted which stated that, in order to achieve the aims of the Convention, 'Contracting Parties should designate as many as possible of their wetlands of international importance for the List'. Increasingly, however, a broader catchment perspective has been developed, in recognition of the many external threats posed to Ramsar wetlands.

The concept of 'wise use' has been developed during the six Conferences of the Contracting Parties and is to be utilised as guidance in the multiple use of wetlands. *Guidelines for Implementation of the Wise Use Concept of the Convention*, developed by the Working Group on Criteria and Wise Use, were recommended for adoption by Parties by the Fourth Meeting of the Parties at Montreux:

> The wise use provisions apply to all wetlands *and their support systems* within the territory of a Contracting Party, both those wetlands designated for the list, and all other wetlands. (Recommendation C.4.10 and Annex. Emphasis supplied.)

This was then further developed and, at the fifth meeting of the Parties, resolution 5.6 – *Additional Guidance for the Implementation of the Wise Use Concept* – was accepted in recognition of the complexity of applying the wise use provisions.

> In the early years of the Convention, the wise use provision proved to be difficult to apply. Most attention was focused upon the designation of sites onto the Ramsar List in line with global priorities to secure the conservation of internationally important areas. Over time, as the essential need to integrate conservation and development has become recognised throughout the world, the Contracting Parties to the Ramsar Convention have made wise use a central theme for the functioning of the Convention. (Resolution C.5.6 (Annex))

The resolution also noted a number of conclusions by the Wise Use Working Group including, at paragraph 5:

> Where wetlands form an integral part of a wider coastal zone or catchment, wise use must also take into account the problems of the surrounding zone or catchment.

3.3 Montreux Record

As with World Heritage Listing, a wetland site can be taken off the Ramsar List or the site may be placed on the 'Montreux Record'. Article 3(2) of the Convention provides:

> Each Contracting Party shall arrange to be informed at the earliest possible time if the ecological character of any wetland in its territory and included in the List has

> changed, is changing or is likely to change as the result of technological developments, pollution or other human interference.

The Article goes on to provide that the information on such changes is to be passed without delay to the secretariat, the Ramsar Bureau. The resulting list has become known as the Montreux Record.

Contracting parties meet every three years, to make new recommendations and resolutions and re-examine listed sites. They are required to arrange to be informed at the earliest possible time if the ecological character of any wetland in their territory has changed. As wetlands constantly undergo a process of natural change, it is important to define technological developments, human interference and the threshold of acceptable/non-acceptable change. Often there is not enough known about a wetland site to determine whether an adverse impact is natural or otherwise.

In the lead up to the Brisbane Conference of the Parties in 1996, a number of the Australian sites were nominated by non-governmental organisations for Montreux listing: the Macquarie Marshes and Towra Point in NSW; Lake Toolibin in WA; and Lake Corangamite in Victoria. Both of the NSW sites are widely recognised as suffering considerable degradation and continuing threats to their ecological character. Environment Australia wrote to the three State Governments seeking comments but State Ministers effectively vetoed the proposal in each case.

Whether listing on the Montreux Record would have gone ahead even if the States concerned had agreed is doubtful. Australia has never used the Montreux Record. The 1996 Australian Report to the Convention on implementation states that no sites have been listed and adds:

> It is the current policy of Australia to solve such problems domestically rather than seek listing on the Montreux Record.

Unfortunately the Montreux Record is often viewed as a 'Hall of Shame'. In fact the idea behind Montreux listing is not only to attract external scrutiny, but to obtain funding assistance for developing countries and to encourage efforts to rehabilitate the wetland site. However, even this view of the Montreux Record has been misconstrued within Australia to mean that the Record is only for developing countries that need to attract external funding to address such problems. There are about 60 sites currently on the Montreux Record, including the Florida Everglades in the United States and several sites in Britain.

4 Implementation of Ramsar in Australia

4.1 Legislation

Australia's 49 sites are situated within a wide range of tenure and protection status. The Ramsar Convention itself is not incorporated by any specific legislation. Implementation is through a range of Commonwealth, State and Territory instruments which directly or indirectly have an impact on wetland management.

Implementation is under the auspices of the Australian and New Zealand Environment and Conservation Council (ANZECC). A working group of ANZECC, comprising officers from each Australian State and Territory ANZECC agency, advises on the implementation of the Ramsar Convention in Australia.

Coordination of implementation at a national level is conducted by the Federal Government's Environment Australia Biodiversity Group. Its Wetlands, Waterways and Waterbirds Unit administers the National Wetlands Program which provides funding to both government and non-government organisations to promote the Ramsar Convention guidelines.

So far as Commonwealth legal initiatives are concerned, regulations can be made under s 69 of the *National Parks and Wildlife Conservation Act* 1975 (NPWCA), 'for and in relation to giving effect to an agreement specified in the Schedule'. The schedule lists a number of international agreements, including the Ramsar Convention. A similar power under s 175(1) of the *Endangered Species Protection Act* 1992 is more restricted in that it only allows regulations giving effect to specified international agreements, including Ramsar, insofar as they relate to the recovery or conservation of *listed* native species or *listed* ecological communities.

The only Commonwealth designation with any claim to national status is listing on the Register of the National Estate under the Commonwealth's *Australian Heritage Commission Act* 1975. Under s 30 of the Act, Federal Ministers must ensure that their departments and authorities do not act in a manner which adversely affects sites on the Register but only about half of the Ramsar wetlands are listed in whole or in part under these provisions. Moreover, listing on the Register of the National Estate only has implications for Commonwealth activity or activities by the private sector requiring Commonwealth approval. It has no implications for day to day management.

Planning and development decisions which may have an impact on wetlands are addressed by environment impact assessment legislation in each jurisdiction, however, there is considerable variation between each jurisdiction and no specific 'triggers' of impact assessment for proposals which could affect Ramsar wetlands.

All State and Territory jurisdictions in Australia have legislation on the creation and management of nature conservation areas in which wetlands may be protected. Queensland's *Nature Conservation Act* 1992 cites international significance as a factor in protecting areas. The *Nature Conservation Act* includes sections dedicated to the management of areas considered to have 'internationally significant natural values' (s57(1)) which can then be declared an international agreement area (s59) and must be managed in a way to maintain its importance (s26).

There is a commitment to cooperation and implementation between the States, Territories and Commonwealth contained in the non-binding Intergovernmental Agreement on the Environment (IGAE) which outlines the responsibilities and interests of the different jurisdictions and the accommodation of those interests by the parties.

Management of Ramsar wetlands may also be subject to wetlands policies. The policies in Australia to date are:

- Commonwealth Wetlands Policy (1997)
- New South Wales Wetlands Policy (1996)
- Western Australian Wetlands Policy (1997)

The Commonwealth wetlands policy only applies to wetlands on Commonwealth land. It is 'hoped that the Policy will provide a model' for other levels of government to follow.

4.2 Political constraints

It is the Commonwealth's responsibility under international law to ensure Australia meets its obligations under international environmental agreements to which it is a party. The multitude of jurisdictions and the consequent conflicting interests and procedures may complicate and hinder implementation but, as noted above, federal systems are not acknowledged as mitigating international responsibility of countries for actions in breach of treaties by its constituent states.

Within Australia, the States have traditionally taken responsibility for much of Ramsar's implementation in the field. The Commonwealth exercises immediate responsibility for sites only in territory within its jurisdiction. The devolution of most environmental responsibility to the States hampers effective and coordinated implementation of Ramsar. This means the Convention is implemented in an uneven manner with Environment Australia overseeing disparate approaches and initiatives.

The State and Territory borders also cut across natural boundaries, raising issues of multiple jurisdictions applying to discrete systems such as catchments. For example, the area contained within South Australia's Coongie Lakes wetland is part of Cooper Creek which originates in Queensland on the Great Divide and flows into the Lake Eyre. However, this has been addressed in Australia to some extent via the IGAE and statutory authorities such as the Murray-Darling Basin Commission.

4.2.1 Role of the Commonwealth

The Commonwealth has authority for exercising an environmental role beyond its existing position and arguably has an international duty to do so in its ratification of international environmental law. Domestically, the IGAE recognises that the Commonwealth's responsibilities and interests include:

> (i)... negotiating and entering into international agreements relating to the environment and *ensuring* that international obligations relating to the environment are met by Australia; (emphasis supplied)

Under the agreement the States 'continue to have responsibility for the development and implementation of policy in relation to environmental matters which have no significant effects on matters which are the responsibility of the Commonwealth or any other State'. The agreement thus reinforces the delineation of duty; the implementation of international environmental law is a Commonwealth responsibility as it is to ensure international obligations are met while the residual environmental matters are left to the States. Further, in Schedule 9 to the IGAE regarding Nature Conservation, clause 10 states:

> The parties agree to cooperate in fulfilling Australia's commitments under international nature conservation treaties and recognise the Commonwealth's responsibilities in ensuring those commitments are met.

It would therefore be open to the Commonwealth to intervene in a State's exercise of environmental policy if international environmental obligations were not met or were contravened. The Commonwealth can legislate with respect to environmental matters and its constitutional authority to legislate to implement an international environmental convention is now well accepted.

However, while there appears to be the capacity for intervention on the part of the Commonwealth, political reality dictates a cautious approach with State Governments anxious to defend their turf from the potential effect of treaties on the federal-state balance of power.

For example, the authority for the Commonwealth to intervene in State environmental matters by way of regulations under the *National Parks and Wildlife Conservation Act* 1975 has been exercised only once: to prevent Tasmania's Hydro-Electric Commission constructing a dam on the Gordon River which was within a World Heritage area. However, there remains a clear reluctance on the part of the Commonwealth to use its constitutional powers other than in a coordinating role in cooperation with the States.

It would be infinitely preferable to have a coherent, coordinated approach to environmental management in Australia. It would avoid bureaucratic duplication, and 'jurisdictional shopping' by developers, while providing greater efficiency, a firm jurisdictional stance and enhanced communication between Commonwealth and state/territory governments. At the same time, it is vital to develop relationships with local stakeholders and to maintain a localised approach.

The reality is that there are different jurisdictions, under which people have different rights and responsibilities. The environment is subject to different legislation and managed by various agencies, which may be resource-based or conservation-based, yet all are dealing with the same issues. There is also a physical reality which must be faced in the implementation of Ramsar.

4.3 Management issues

The Ramsar Convention provides for 'wise use' of all wetlands, but implementation of the Convention has tended to focus on setting aside icon areas. What is actually needed is cross-jurisdictional and landscape management of the entire wetland, including the surrounds of each Ramsar site.

Issues relating to the management of the Macquarie Marshes, a Ramsar-listed site in NSW, serve as an excellent illustration of the need for planning to be carried out in the context of the whole catchment, rather than determined by the limits of Crown land. This wetland in the north west of the State covers more than 150 000 hectares and comprises a complex of swamps, channels and floodplain. The area designated as a Ramsar site in 1986 is, however, restricted to the existing nature reserve which is only 18 143 hectares, or 14 per cent of the marshes. Many of the bird breeding colonies are located on privately owned areas of the wetland.

The main land use here is cattle grazing, but there is one cotton farm which relies on irrigation water. Upstream from the Marshes, there is extensive cultivation of irrigated cotton. This has led to a sometimes bitter struggle for water between upstream cotton irrigators, on the one hand, and an uneasy alliance of cattle graziers and conservation interests, on the other.

While there are a number of Ramsar-listed wetlands on private land (such as in Tasmania where of its ten sites one is entirely on freehold land and three are partly freehold) the great majority are on Crown land. There have been no conservation measures taken with regard to Tasmania's privately-held sites, all of which were listed in 1982 without prior consultation with the affected landholders. The challenge for management agencies is to ensure that the Convention's principles can be applied to listed sites, no matter what their tenure. The Convention does require wise use of *all* wetlands but for the management personnel trying to deal with a range of tenure on listed sites and a range of responses to international law, from acceptance to suspicion to hostility, then any degree of influence over land use if only on the Ramsar wetlands may be considered a relative blessing. Attempts to negotiate management guidelines with the landholders for the Tasmanian wetlands are 'ongoing'.

In NSW all six Ramsar sites are wetlands which were already protected within national parks or nature reserves.

4.4 Private land management

While Ramsar listed sites have tended to be on Crown land, there is greater acceptance now of the need to confront the issue of private land management. After all, 500 million hectares is managed by private landholders, compared to 40 million hectares within the terrestrial reserve system. A broader focus is envisaged by the Convention and a total catchment approach is required. This approach will be more complex and resource intensive, and politically difficult due to the need to overcome an entrenched private land ideology and the complex issue of water rights and water allocation. The possibility of compensation has been raised, but will be complex and very expensive. It has been suggested that a far more positive approach is to develop stewardship practices where people are paid on an ongoing basis to look after their land. It is a forward-looking system based on the extent of management activity required and carried out, rather than loss of market value of the land. Stewardship could be more equitable than compensation because it is based on work performed rather than on what may be chance factors. This is a very localised approach and we hope that International Law here, the Ramsar Convention in particular, could help persuade the Commonwealth Government to recognise its obligations to wetlands, and the need to include private land to maintain catchments and to conserve our wetlands.

5 Questions

Question: *With those wetlands in Tasmania, what are the chances of success for some of them remaining at a high conservation value if you take the sort of approach in which you include private land?*

Tasmania did eventually realise that it probably wasn't the greatest approach. I mean it was quite a brave approach, but of course they could have got right up the noses of the farmers who would perhaps have just drained the wetland and filled it, or whatever, just because they were so irritated. Now there is a process of negotiation. New South Wales has been very 'softly-softly' about this and as a result there is no privately-held Ramsar site in that state. Tasmania probably went a little too far the other way and, yes, you should have negotiation. It's a general problem; international law doesn't get very good press generally, especially with the ongoing sensitivity with regard to 'States Rights'; the Commonwealth is seen as making a power grab. There are issues of sovereignty at a number of levels: international bodies to nation states, nation states to constituent states, governments to private landholders. You are going to have that same issue all the time, and it is the issue of defending one's sovereignty: 'This is my land, bugger off, don't tell me what to do'. It's a major constraint in the effective application of International Environmental Law.

Question: *I've got an example to back up one of your points. A couple of years ago I was invited over to Maningrida to explain Ramsar to them and they had never heard of Ramsar. We were there for three days, and at the end of it they said 'well, it's got nothing to offer us, it doesn't do anything we don't already have so far as security is concerned'. The only answer I came up with was that we can offer them greater money opportunities.*

Yes, the funding provides people with some sort of incentive to see a value in it, so perhaps it is a good thing that it provides that connection which may lead to other elements of the Convention being embraced. Another positive aspect to the funding is with regard to the role of the Commonwealth which usually doesn't seem willing to exert a strong hand regarding wetland management in the other jurisdictions. But if they are giving money out then they are a little more touchy about what's happening to their funds, with expenditure at least ostensibly constrained by the National Wetlands Program guidelines which in turn comply with the Convention's objectives.

Question: *With the stewardship process, can you elaborate and give a practical example of where it has worked?*

Under Queensland's *Wet Tropics World Heritage Protection and Management Act* 1993, the Wet Tropics Management Authority (WTMA) can enter into cooperative management agreements under which the landholder might, in return for payments, agree to land use restrictions beyond those ordinarily applicable under the Wet Tropics Management Plan, and would actively manage the land.

Cooperative management agreements have been negotiated with a number of landholders. The agreements so far signed off have included a number of trade-offs. For example, one landholder who wished to convert two leaseholdings to freehold title agreed to a number of stewardship obligations in return for which the Authority would offer no objection to the freeholding. The conditions agreed to by the landholder included:

- conserving the biological diversity and ecological integrity of the land;
- not destroying native vegetation on the land without the prior written approval of the Authority (approval only to be given if the vegetation is a threat to public safety or to property);
- not allowing any species listed as undesirable plants to grow on the land;
- ensuring that no cat is kept on the land;
- allowing pedestrian access across the land to members of the public wishing to use the walking track to a waterfall on the property.

The landholder can also nominate areas to be revegetated back to their natural state. The Authority will provide advice and, at its discretion, material assistance.

Another example of a cooperative management agreement involved landholders who wished to re-establish native rainforest on part of their land that had been cleared. They and the WTMA agreed to enter into an agreement to allow the revegetation work to proceed. The Authority agreed to fund the revegetation and three years' subsequent maintenance of the land, including fencing of the area. In return the landholders agreed to similar conditions as outlined above as well as providing ongoing maintenance of the revegetated area.

Question: *Who establishes the criteria used to determine the definition of 'wise use'?*

It is generally quite abstract, where you say 'wise use' is going to be 'sustainable use of the wetland', and that decision is made by policy and/or management personnel in each area. Because a lot of these sites are on reserved land, it may simply be how the site would be managed anyway, and each jurisdiction will decide that for themselves.

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Wetland management – sectoral divides and underlying issues: a case study based on the invasion of wetland by other weeds

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Abstract

The causes of wetland loss and degradation are not independent. Management planning and monitoring to address these causes need to bear this in mind. The main apparent reasons for wetland loss and degradation are changes in wetland area, changes in the water regime, changes in the water quality, unsustainable exploitation of wetland products, and the introduction of alien species. Invariably, these causes are addressed on a sectoral basis with few examples of constructive and long running cooperative management approaches. If the rate of wetland degradation in northern Australia is to be halted we will need to urgently address the social, economic and political underlying reasons and not just the apparent expressions of the reasons for such degradation. At an international level the underlying reasons include population pressure, lack of public and political awareness of wetland values, lack of political will for wetland conservation, over-centralised planning procedures, financial policies and irregularities. A formal assessment of the relative importance of these underlying reasons in northern Australia has not occurred. The more immediate causes of wetland loss and degradation relate to weak conservation institutions, sectoral organisation of decision making, deficiencies in the application of environmental impact and cost-benefit analysis, the passing of good legislation without subsequent enforcement, a lack of trained personnel, limited international pressure, and alliances which promote studies rather than action.

Key words: wetland loss, degradation, weeds, management planning, monitoring, sectoral divides

1 Introduction

Comprehensive information on the extent of wetland loss and degradation in northern Australia is not available. Further, most of that which is available addresses the apparent reasons for wetland loss and degradation (such as weed invasion, drainage) and not the underlying socio-economic and political reasons (Finlayson et al 1998a). The apparent causes of wetland loss and degradation include activities that directly affect the ecological character of the wetland. These are, in fact, manifestations of the underlying causes of wetland loss and are generally inseparable from the pressures of population growth and further economic development. Major causes of wetland loss and degradation in northern Australia are given in Bunn et al (1997). To prevent further ecological change. the underlying and often invisible factors, the immediate policy and institutional elements, and the more apparent and almost always highly visible causes of adverse ecological change in wetlands must both be addressed (Hollis 1992).

General information on the underlying reasons for wetland loss and degradation can be found in Hollis (1992), Finlayson (1994), Hollis and Finlayson (1996), but there is little information specific to northern Australia. Thus, in addressing current management issues for wetlands in northern Australia little mention is made of the underlying socio-economic and political factors that greatly affect management processes and decisions (Storrs & Finlayson 1997).

Current uses of wetlands in northern Australia include: pastoralism, grazing, horticulture and commercial fishing; tourism and recreation, especially amateur fishing; conservation and nature reservation; and traditional subsistence. These land uses are most intensive in the seasonally inundated and very productive wetlands near Darwin in the northern coastal region.

The utilisation of wetlands and wetland products raises a number of specific and general concerns for conservation and land/water management agencies. Access to and maintenance of the ecological character of the wetland habitats have received a great deal of attention and been subject to land use planning and zoning. However, often this has been done on a sectoral basis with little regard for other sectors or groups within society. Within this scenario, however, sectoral divides and associated underlying socio-economic and political issues that affect land use are being seen more and more as the prime reasons for ineffective wetland management (Hollis 1992, Finlayson 1994, Hollis & Finlayson 1996). An overview of these issues is presented below along with the specific example of weed invasion of wetlands.

2 Sectoral management

Sectoral management of wetlands is neither new nor the prerogative of any one group or country. It is widespread (see Hollis 1992, Finlayson et al 1992, Kvet 1992, Jonauskas 1996). In talking about wetlands of the Mediterranean basin Hollis (1992) made the following statements:

> *"........... a solution to the problem of wetland loss and degradation .... will not be found by tackling only the apparent causes of the problem."*

> *" .... all of the problems need to be tackled simultaneously and immediately, at all levels .... "*

> *"There has to be an offensive on the social, economic and political causes of wetland loss and degradation......"*

Recent assessments of the extent of wetland degradation in northern Australian wetlands (Finlayson et al 1998, Finlayson & Storrs 1997) provide evidence that these statements are readily transferable. Thus, if the extent of wetland degradation in northern Australia is to be halted we will need to urgently address the social, economic and political underlying reasons and not just the apparent expressions of these reasons (ie the impact of the weed, feral animal, pollutant or land use).

The major reasons for degradation of wetlands have increasingly been grouped along the following lines (Dugan 1990, Hollis & Finlayson 1996, Bunn et al 1997)

- changes in wetland area
- changes in the water regime
- changes in the water quality
- unsustainable exploitation of wetland products
- introduction of alien species

Management of these problems has often been assigned to individual and separate agencies with relevant expertise, but with little incentive or aptitude to cooperate openly with other agencies, landholders or users. This problem is not peculiar to northern Australia. Attempts to develop multi-functional agencies have been made, but it is still widely recognised that poor communication and sectoral attitudes still persist. Attempts have been made to overcome such problems with joint and/or interagency advisory committees and technical panels and at a governmental level some success has been achieved. The attempts to address the severe environmental problems on the Lower Mary River in the Northern Territory have exemplified one such approach (Jonauskus 1996), but it is no secret that inter-sector problems still exist.

A similar conclusion was made by Bayliss et al (1998) in an assessment of the vulnerability of the wetlands of Kakadu National Park to climate change and sea level rise. The wetlands of Kakadu have recognised conservation values. However, they are under threat and many of the problems can not be managed without a high level of cooperation between the park authority, local traditional owners and users of the park, plus representative groups and agencies from around van Diemen Gulf. The wetlands are interconnected (Storrs & Finlayson 1997) and can not be managed in isolation (Bayliss et al 1998, Storrs & Finlayson 1997). In response to this situation the Environmental Research Institute of the Supervising Scientist has established a monitoring node for collating and assessing the information resource and monitoring change in the wetlands of Kakadu. It is anticipated that this monitoring node will have sufficient utility to be transferred to neighbouring lands. This project is overseen by a broadly based group of landholders and users and governmental agencies. However, this node has a research and monitoring function only, it is not a management structure. The issues of managing across this broad area with at least four different land jurisdictions (private and Aboriginal leasehold, Commonwealth and Territory conservation reserves) have not similarly been addressed (Finlayson et al 1998b).

A further example of the complexities of sectoral divides is shown by the utilisation of the concepts and instruments of the Ramsar Convention for Internationally Important wetlands. A recent informal assessment (L. Tucker pers comm) has highlighted the low-level, if not absence in many instances, of knowledge of the listing of internationally important wetlands in the van Diemen Gulf region. Further, the obligations and instruments available to managers under this convention are not well known. This is in total contrast to Australia's input at the international level. To be truly effective the values that derive from participation in such a convention need to be relayed to all interest groups. At the same time it is also worthwhile pointing put that several Aboriginal communities in Arnhem Land have made informal inquiries about listing their wetlands as internationally important under this convention. Thus, the information is obviously available, but is not being evenly distributed or utilised. The challenge is to make the relevant information available to all parties in a manner that they can readily utilise. Current sectoral divides have hindered this process and possibly retarded the development and/or adoption of management attitudes and methods.

3 Underlying reasons

Hollis and Finlayson (1996) point out that the root cause of continuing wetland loss and degradation in the Mediterranean basin are

- population pressure
- lack of public and political awareness of wetland values
- lack of political will for wetland conservation
- over-centralised planning procedures
- financial policies and irregularities

Further, the more immediate causes relate to

- weak conservation institutions
- sectoral organisation of decision making

- deficiencies in the application of environmental impact and cost-benefit analysis
- the passing of good legislation without subsequent enforcement
- a lack of trained personnel
- limited international pressure
- and alliances which promote studies rather than action.

A similar analysis has not been undertaken in northern Australia, but many of the above issues have been highlighted in recent reviews (Bunn et al 1997, Storrs & Finlayson 1997, Finlayson et al 1998a).

The processes that result in wetland loss and degradation are, in fact, manifestations of the underlying causes and are generally inseparable from the pressures of population growth and further economic development. The major processes causing wetland loss and degradation on a global basis are

- agricultural (including irrigation) intensification
- urbanisation and industrialisation
- tourism and recreation
- expanding fisheries and aquaculture
- hunting activities

Again, without having a formal analysis these processes have been recognised as important in northern Australia (Storrs & Finlayson 1997, Finlayson et al 1998).

Whilst these processes are listed separately they are not totally independent. For example, water pollution can be caused by industrial and agricultural practices as well as tourism and aquaculture developments. Increased tourism can also lead to the conversion of wetlands to resorts. The intensification of agriculture through irrigation, booming tourist resorts and burgeoning cities and rising demand for electricity can combine to create dams and water supply schemes which have a radical effect on downstream wetlands. This interdependence must be borne in mind when drawing up management plans and monitoring programs to address the causes of wetland loss and degradation.

4 Underlying socio-economic and political reasons for weed invasion

As previously discussed (see Storrs weed management paper this volume) there are ecological reasons that mean that NT wetlands are susceptible to invasion by weeds. They seem to be intrinsically susceptible to invasion through 'natural' disturbance and they have also been disturbed through anthropogenic activities, eg invasion by feral animals (Rea & Storrs 1998).

NT wetlands have received relatively few weed species but weeds are spreading through Australia faster than they can be controlled and it is expected that new weeds will enter Australia and the NT over the coming years (Humphries et al 1991). The underlying reasons for this are often socio-economic or political (Rea & Storrs 1998). Some of these reasons are addressed below.

4.1 Bureaucratic frameworks and responsibilities

4.1.1 Development

The NT economy is in a development phase, based firmly on using natural resources. Wetlands in the Northern Territory are managed under a multiple land use policy that seeks to '*... maintain biological diversity and other natural resources, plus promote ecologically sustainable development*' (Fleming

1993, Fulton 1995). Thus wetlands are recognised for both their conservation and economic values. The policy attempts to encourage different land uses and to provide a balance with conservation objectives.

With accelerating rates of economic development in the Top End, wetland use and conservation issues are being brought into conflict (Whitehead et al 1990, Janouskas 1996). One of the prime examples is the introduction of ponded pasture species. To support pastoralism, the NT government has been encouraging the planting of introduced ponded pasture plants (Lemcke 1996).

The introduction of these grasses ignores advice that these plants may become major environmental weeds (Clarkson 1995). The introduction of these exotic grasses is also questionable from a needs basis. Native grasses can be very nutritious (Calder 1981) and, prior to BTEC, native pastures were able sustain vast herds of buffalo; up to 7 animals per ha (Bayliss & Yeomans 1989). The total NT buffalo herd of approximately 341 000, was about the same as the domestic cattle herd (Bayliss & Yeomans 1989). The introduction of ponded pasture species is proceeding without ecological risk assessment or environmental cost-benefit analysis.

Wildlife values and their contribution to commercial activity (eg tourism) should be explicitly incorporated in any cost benefit analysis (NT Government 1995). For the policy of multiple use to be sustainable, authorities and stakeholders need to be aware of the effect of their actions on wetlands and other land users (Rea & Storrs 1998). As multiple use of NT wetlands is in its early development, now is the time to gain a commitment from all stakeholders to accept some constraints on the achievement of their narrower goals whilst community wide stakeholder consultation is increased (Rea & Storrs 1998).

4.1.2 Planning

Tackling weeds in the expansive natural areas of the sparsely populated Top End necessitates a strategic approach (Storrs & Lonsdale 1995, Storrs et al 1996). Case studies have shown that carefully planned ongoing management of introduced species, is more likely to succeed than short-term, intensive control (Usher 1988). An NT Weeds Management Strategy (NT Government 1996) has been developed which calls for government to work with land holders and land managers to plan and implement weed management on a catchment basis over the long-term.

Apart from regional strategies (eg Storrs 1996), individual holdings need weed control integrated into Property Management Plans, which set out realistic frame-works for the future (Rea & Storrs 1998). Property Management Plans have been strongly adopted in southern Australia and are intended to overcome ad hoc weed management: that is, controlling weeds when money allows, when situations become critical or on a seasonal basis. The draft NT Weeds Management Bill proposes that the requirement for Weed Management Plans could be enforceable by Government authorities.

Although Aboriginal people own much of the floodplain country, learning from indigenous land use and experience has not featured in their utilisation. One of the most exciting things happening at the moment is the Environment Australia-funded project to produce management plans for 10 important wetlands on Aboriginal land - *The Top End Indigenous Peoples Wetlands Program* (see Storrs community wetland management paper this volume). It is a great example of cooperation between individuals and agencies. The program commenced in early 1996 and adopts a strategy of 'total catchment management' coordinated between regions. At the local level the community has control of, and participates in, the planning process and implementation phase of wetlands management.

4.1.3 Sectoral responsibility

In the Top End, weed control is largely dictated by land tenure and the commitment, financial capability, and management preferences of responsible agencies (Rea & Storrs 1998). Apart from private (freehold or leasehold) and Crown land, there is significant Aboriginal ownership (~85% of the

NT coastline), as well as Commonwealth and Territory administered land. These boundaries are transgressed by weeds.

The multisectoral problem is well illustrated by mimosa control in the Top End. A litany of problems, ranging from experimental biological control plots being sprayed with herbicide, to non-strategic management of large-scale infestations, is the result of different management objectives and poor cooperation. A Territory-wide strategy is needed to bring together different land-owners and land-managers, and to make knowledge on control freely available and unrestricted by agency protocol (Rea & Storrs 1998).

The draft NT Weeds Management Bill proposes that as well as an NT Weed Management Committee being appointed, regional (or catchment based) or specific purpose weed management committees be established.

4.1.4 Accountability

Those utilising wetland resources need to be responsible for their impacts, in the same way mining companies are required to conduct environmental impact studies, operate within a set of guidelines, treat waste and rehabilitate their mine-sites (Finlayson 1991). Until government, industries and managers are held accountable for the impacts of their decisions and activities, then weed problems can be expected to increase. Accountability would lead to more effective weed management and control (Rea & Storrs 1998).

When problems are truly incurable, short-term control can also make situations worse. For example, one-off chemical treatments or continuous ad hoc attempts to control mimosa mechanically and with fire, appear to actually increase its growth and reproduction.

In addition, the consequences of control measures such as excessive herbicide use can lead to new and more serious problems (eg excessive herbicide use, toxicity and resistance), which can override the initial weed problem. The argument for doing something, is only warranted if real benefits accrue. Being seen to be doing something should never be a reason for undertaking weed control (Rea & Storrs 1998).

4.1.5 Resources & Funding

Weed research is often undertaken with funds allocated under a short-term contract framework, with continuation contingent on outcomes (ie improved weed control). However, outcomes to environmental problems are usually achieved over the long term (Rea & Storrs 1998).

Mimosa is seen to be one of the most important weed threats to Australia. However the CSIRO/DPIF biological control program workers in Darwin and Brisbane, are continuously under funding constraints and threats of closure. Research staff have spent a lot of time obtaining support and writing proposals as well as fighting political battles. In that situation how can effective research be undertaken? Only with substantial and secure funding, can researchers be truly effective.

The nature of governmentspending is another reason behind continued degradation of Top End wetlands (Rea & Storrs 1998). Present expenditure is heavily weighted toward chemical control, and to a lesser extent, biological control. Where chemical control is expensive and unsustainable in the long term, biological control is a long term solution that is environmentally sensitive and cost-effective. As well, mechanical and ecological control are often practised by 'trial and error' and not supported by substantive research investigations (Rea & Storrs 1998).

The $8 million Oenpelli spraying campaign was largely designed to attract government funds (Rea & Storrs 1998). Addressing weed issues with large one-off control programs may appease community concern, satisfy industry stake-holders, fit in with the 'commercial' cycle of government spending and have spin-offs for local economies, but it is not conducive to the successful management of environmental problems.

If improved weed management is the ultimate objective, new ways of funding environmental issues are needed. Self-regulation of funds as investments in long term trusts, would provide continuous finance and in theory lead to more efficient and effective weed control (Rea & Storrs 1998).

Government funding of weed research and management can never be sufficient to resolve problems on behalf of industry. The industries which utilise Top End wetlands (ie pastoralism, tourism, fisheries, wildlife harvest) are yet to contribute funds to mimosa or salvinia research and management. Yet, all stand to benefit from Territory and Federal government funds.

Ultimately, it is taxpayers money that is footing the bill for weed problems which industry practises may have contributed to in the first place. Stakeholders should be encouraged to invest in Research and Development of environmental problems, rather than expecting others to pay (Rea & Storrs 1998). Accountability and mandatory sustainable land management should be strong incentives.

4.2 The generation and application of information

4.2.1 Awareness

It is critical that the whole community is aware of the significance of wetlands and the detrimental effects of weeds. As discussed, in general, most economic development proceeds without consideration of the potential ecological impacts. Only after visible and detrimental impact to people, does research on impact assessment and measures to ameliorate change usually begin.

Ownership of weed problems are often limited to people whose livelihood depends on wetlands or live in their vicinity. For others, the inaccessibility of wetlands lends an 'out of sight out of mind' attitude, such that their value is easily misunderstood. The small population in the Top End and extensive natural areas, may sustain the attitude that we can still afford to sacrifice some country (Rea & Storrs 1998).

However, wetland protection is needed on large scales because of the gentle gradients that cover wide distances, and because diversity in this region, is held in the high degree of spatial and temporal pattern, which provides food, shelter and nest sites for many animals (Whitehead et al 1990). As weeds threaten the high diversity and richness of animal species, notably birds, which are the principal foci for tourism in the Top End, they can have significant economic impact. Wider appreciation of these links would provide support for ecologically sensitive land use.

DPIF has long been producing a series of posters and calenders for distribution. These are strongly supported and should be circulated widely amongst land owners and users especially Aboriginal communities. But much more is needed – there is a need to seek relevant professional advice on the most appropriate means of transferring information (eg role of regional or local newspapers, community radio and television etc (Storrs & Finlayson 1997). Once various media have been identified the nature of the message and the target audience needs analysis. This might fall into the realm of publicity and public relations experts.

4.2.2 Research

With a few exceptions Top End wetlands are poorly understood with little information on processes and functions in the wider landscape (Storrs & Finlayson 1997). Many studies have been of short duration and there are no multi-disciplinary long-term programs. In some cases, valuable ecological information has not been placed in the public domain by government and private sectors. This lack of theoretical frameworks and insufficient ecological information for wetland management, may indirectly allow weeds to persist and spread (Rea & Storrs 1998).

Wetland specialists and managers are being asked to quickly find solutions to weed invasions and provide advice about sustainable ecological management. However, there is limited data from which to draw; the closest coming from the control of agricultural weeds in different regions. This is why herbicides are often used at the outset. Translating agricultural experience to the management of ecological problems may result in new problems (herbicide resistance, toxicity, reduction in biodiversity), which land-owners and managers need to be aware of before operations proceed.

Calls for assessment of the ecological impacts of weeds and environmental impact assessment of control operations have been around for a long time (eg Mitchell 1978). In the Top End, few weeds have had their ecological impact assessed at any level, despite such information being essential before control operations begin.

Control programs for mimosa and salvinia have proceeded without any risk analysis, environmental impact assessment, or cost benefit analysis (Rea & Storrs 1998). While the costs, efficacy and impacts of integrated or individual methods are unknown, resources are expended without a full knowledge of the outcomes.

4.2.3 Communication

The majority of weeds require persistent, long-term, low-key control. The widespread use of the term 'eradication' undermines control strategies by promoting cynicism and misunderstanding (Rea & Storrs 1998). Although the Kakadu National Park Plan of Management (ANPWS 1991) states the aim of eradicating all weeds from the Park, the basic message for salvinia, after a three year ecological study, is 'learn to live with the weed' (Storrs & Julien 1996). Essentially, short-term control often has little real effect, and runs the risk of causing environmental degradation. Realistic integrated management plans with an emphasis on any positive result as a bonus, will avoid confusion over expectations of eradication.

4.2.4 Prevention

In Australia it is often the case that weeds are 'allowed' to invade. Plants that became weedy were, on most occasions, introduced intentionally for other purposes (Lonsdale 1994). As previously stated mimosa, salvinia and ponded pasture grasses were all deliberate introductions. Ecological risk assessment should be mandatory for all exotic plants (eg pastoral, nursery, cut flower, aquarium), with those qualifying as potential weeds being refused entry into Australia or distribution between biogeographic regions (Rea & Storrs 1998). Ways to predict weediness from plant traits are assisting in the development of strict guidelines and preventative strategies at the national and international level with regard to trade, transport and quarantine (Panetta 1993, Pheloung 1995).

Prevention also covers intrinsic measures that address the cause of weed problems such as reducing grazing pressure, reinstating natural water regimes, reducing nutrient run-off, 'no go' areas, and providing stock and vehicle wash down facilities. These measures are sometimes made to look unfeasible and impractical, despite advice to the contrary. In contrast to quick and flashy aerial spraying from helicopters, they are more time-consuming, requiring thorough and committed management (Rea & Storrs 1998).

Awareness and education programs would assist in the establishment of these changes to management practises. When the logistics are overcome, there are significant long term advantages.

4.2.5 Integrated control

Weed management should 'ideally consist of different control techniques integrated into a flexible program that is suited to local conditions'. There is much scope for developing 'Integrated Weed Management' (Rea & Storrs 1998). Integrated control is where one or more methods are used to make the plant more susceptible to another method. For example, it is hypothesised that mechanical control and fire, both predispose mimosa to more damaging attack from biological control agents. Investigating the impact of, and interaction between, control methods will lead to better weed management.

Information about the ecological and biological responses of weeds to the environmental characteristics of the habitats they invade, should enable targeting of control methods for better effect. Although frequently touted as the best approach, integrated control is little adopted in the NT, due to lack of information and commitment. The proposal for the integrated control of salvinia in Kakadu National Park (Storrs & Julien 1996) is a rare example of an integrated weed strategy in the world.

4.2.6 Rehabilitation

Degraded wetlands can be made more resilient to weed invasion through the planting of competitive species. However as there are broad differences in the reasons for managing weeds there are also different ideas about post control rehabilitation. The objective on NT and Commonwealth Reserves is to reclaim native vegetation and wildlife for conservation, tourism and fisheries while the pastoral industry aim to replace weeds with productive grazing pasture. For example, in the Mary River system, 1200 kg of replacement vegetation seed was aerially distributed at the same time as herbicides in 1995/96. Most of it was non-native species such as commercial rice and ponded pasture species (G. Schulz pers comm).

Objectives need clarification and rigorous assessment to confirm they are realistic, and in the case of pastoralism, that one weed is not replacing another (Rea & Storrs 1998). There is also a need to complement control and rehabilitation with an effective monitoring program, which can help prevent further seed germination and plant invasion.

5 Conclusion

Introduced flora and weeds, are just starting to get the attention they deserve. The overriding goal of wetland weed management should be to prevent further loss and degradation of wetlands. There needs to be concerted discussion at the national level about what sort of country we want Australia to be in the future.

Australia has the luxury of having natural wetlands and other ecosystems to protect. We remain optimistic that if some of the obstacles and opportunities outlined in this paper, are removed or taken up, respectively, then weed management and wetland protection can vastly improve.

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Management and ecological risk assessment

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Abstract

The degradation and loss of wetlands is a global issue, and in many cases can be attributed to anthropogenically-related factors such as altered water regimes, physical modifications, the invasion of exotic species, and pollutants. With the increase in recognition of such problems, the last two decades have seen a growing emphasis towards sustainable management of the environment, whereby both ecosystem health and the quality of human life can be maintained. Towards achieving this, an understanding of the type and magnitude of stressors an environment can or cannot tolerate is required. One way of determining or estimating this is by a process known as ecological risk assessment (ERA), which involves the estimation of the likelihood of adverse environmental effects occurring as a result of exposure to a stress, usually through human activity. Ecological risk assessment is a series of steps; *problem formulation*, *effects characterisation*, *exposure characterisation*, *risk characterisation*, *risk management*, and *monitoring*. The first step involves the collation of information on the nature of the problem and developing a plan for the remainder of the risk assessment based on this information. Effects and exposure characterisation represent the analysis phase of the risk assessment, where data concerning the responses of the environment to the stressor, and the likely level of exposure to the stressor are gathered. Risk characterisation involves the comparison of effects and exposure data, to estimate the likelihood of adverse ecological effects. Risk management is the process of decision-making based on the results of the risk assessment, which attempts to minimise the risks without compromising other societal or community benefits. Finally, monitoring must be implemented in order to assess the effectiveness of the risk management decisions. This discussion deals with the specific details of each of the above steps of ecological risk assessment, particularly with regard to the potential impacts of pollutants on aquatic ecosystems. Following this, it provides some guidance on how ecological risk assessment can be applied to wetland ecosystems.

Keywords: ecological risk assessment, wetlands, aquatic, chemical stressors, risk management

1 Introduction

Aquatic environments are under ever-increasing pressure from human activities. Many aquatic ecosystems, including wetlands, have already been degraded through urban and industrial development of coastal areas and inland waterways. Such degradation is due to a multitude of anthropogenically-related factors. Physical alterations and habitat modification, such as the draining of wetland areas for urban development, or the damming of rivers for water supplies and agricultural purposes have impacted significantly on Australian aquatic ecosystems (Bunn et al 1997). In addition, the introduction of exotic species has had a dramatic effect on both marine and freshwater ecosystems throughout Australia (Bunn et al 1997). Several examples of animal introductions include the European carp, *Cyprinus carpio* and the mosquito fish, *Gambusia affinis* into temperate freshwater habitats, water buffalo into tropical wetland habitats, and an array of exotic species into marine habitats via the release of ballast water from ocean-going ships. Exotic plants have also caused widespread degradation of waterways and wetlands, particularly *Mimosa pigra* and *Salvinia molesta* in northern Australia (Miller & Wilson 1995). In addition to the above causes of environmental degradation, pollutant inputs into aquatic ecosystems have also been a significant contributing factor in Australia (Bunn et al 1997), although probably not to the extent of that in more industrialised countries in Europe, Asia and North America. Nevertheless, pollutants are still of major concern in Australia for several reasons; the unique faunal groups represented and the lack of knowledge regarding their tolerance to xenobiotics; the seasonal/environmental extremes exhibited within and between regions; and also the fact that along with changes in habitat and water regime, future industrial and urban development will also bring with them the threat of further pollutant impacts (van Dam et al in press).

With the pressure of anthropogenically-related stressors on the environment currently at its greatest, and likely to intensify in the future, the last two decades have seen a growing emphasis towards proper, or sustainable management of the environment, whereby both ecosystem health and the quality of human life are maintained (Cairns & van der Schalie 1980, Stortelder & van de Guchte 1995). Short term gains in the quality of human life can, and have been made at the expense of ecosystem health, but ultimately, such a situation cannot be sustained. For effective environmental management, an understanding of the type and magnitude of stressors that an environment can or cannot tolerate is required. In addition, potential effects of anthropogenically-related stressors on the environment need to be characterised, and weighted against economical and/or societal benefits. A process which serves to achieve this is known as risk assessment, or more specifically, ecological risk assessment.

The remainder of this discussion presents an overview of the process of risk assessment, with an emphasis on ecological risk assessment and its application to wetland research and management.

2 Defining risk assessment

The concept of risk assessment originated from the insurance industry, estimating probabilities and magnitudes of undesired events, such as human mortality, morbidity, or even property loss (Suter 1993). However, it has since spread into a variety of other fields including engineering, toxicology, epidemiology, and economics (Suter 1993).

Risk assessment can be defined as a structured process involving the estimation (qualitative or quantitative) of the likelihood of clearly defined adverse effects occurring as a result of exposure to a stress, usually through human activity (Suter 1993). It estimates the likelihood of harm to humans or the environment (van Leeuwen 1995a) and allows managers to make decisons based on that likelihood.

In brief terms, the process of risk assessment involves: 1) identification of the nature of stressor; 2) determination of the likelihood of adverse effects due to the stressor; 3) determination of the consequences of such an event; 4) estimation of the risk and its acceptability; and 5) management of the risk. Risk assessment need not be directed exclusively at chemical contamination, and thus can be used to assess risks associated with other forms of human activity such as physical disturbances (eg deforestation; van Leeuwen 1995a) or even natural occurrences (eg climate change, fire). However, the majority of this discussion refers to the risk assessment of chemical contaminants.

2.1.1 Human health risk assessment (HRA)

Historically, risk assessments have emphasised the risks of hazards to human health (Suter 1993; Vermeire & van der Zandt 1995). Human health risk assessment (HRA) has usually been associated with the effects of chemicals on humans. Chemicals which are assessed include drugs for use in medicine, general workplace chemicals such as solvents and pesticides, and industrial pollutants.

The major characteristic of HRA, and the one that separates it most from ecological risk assessment, is that it focuses on the protection of only one species, *Homo sapien*. Although, most toxicity data for HRA are derived from standard laboratory test species (eg rodents), and then extrapolated to potential human health effects, the ultimate interest in the health of only one species eliminates much uncertainty in the results. Extrapolation of animal data to humans is usually done by extrapolation of the dose of a no-observed-adverse-effect level (NOAEL), based on body weight, and the use of a safety factor, usually 100 (Kroes 1995). This apparently accounts for the uncertainty in the extrapolation procedure (Kroes 1995). Therefore, uncertainty is mostly limited to variations in exposure routes (ie dermal, inhalation, ingestion) and intra-specific variation (van Leeuwen, 1995a; 1995b).

2.1.2 Ecological risk assessment

With man's bias towards assessing the risks of hazards to human health, effects on the natural environment have largely been ignored. Previously, there has been a common but mistaken belief that protection of human health automatically protected non-human health (Suter 1993). This has since been shown not to be the case, particularly for certain chemicals known to be particularly non-toxic to humans, but found to be very toxic to aquatic life (eg chlorine, aluminium; Suter 1993). In addition, stressors such as physical disturbances (eg deforestation, river flow regulation), not associated with chemical contaminants, will have severe effects on the natural environment, but not necessarily on human health.

The US EPA (1992) defined ecological risk assessment as:

> *a structured process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors*

While a number of different frameworks exist for ecological risk assessment, they generally follow a similar series of steps, as summarised below. However, there are some variations within the literature as to exactly how the process of risk assessment is structured. For example, Suter (1993) incorporated both the assessment process and the process of decision making based on the results of the assessment, termed risk management, in the overall risk assessment process. In contrast, van Leeuwen (1995a) attempted to separate the processes of risk assessment and risk management, although still recognised the inter-relatedness of the two. The US Environmental Protection Agency offer another modification of the risk assessment paradigm (US EPA 1998). For the purposes of this discussion, a slightly modified risk assessment framework is described, incorporating information from Suter (1993), van Leeuwen (1995a) and US EPA (1998).

The process of ecological risk assessment can be divided into the following steps:

1. Problem formulation
2. Effects characterisation
3. Exposure characterisation
4. Risk characterisation
5. Risk management and reduction
6. Monitoring

The above steps are represented as a flow diagram in figure 1, while table 1 gives the definitions of some of the terms commonly used in risk assessment, including those of the above steps. Further details regarding the steps of ecological risk assessment are discussed below in section 3.

Although highly structured, ecological risk assessment is a flexible process for collecting, organising and analysing data, information, assumptions and uncertainties in order to estimate the likelihood of adverse ecological effects (US EPA 1998). As such, it provides a framework that allows effective analysis and decision making based on the analysis, while also providing an adequate mechanism of

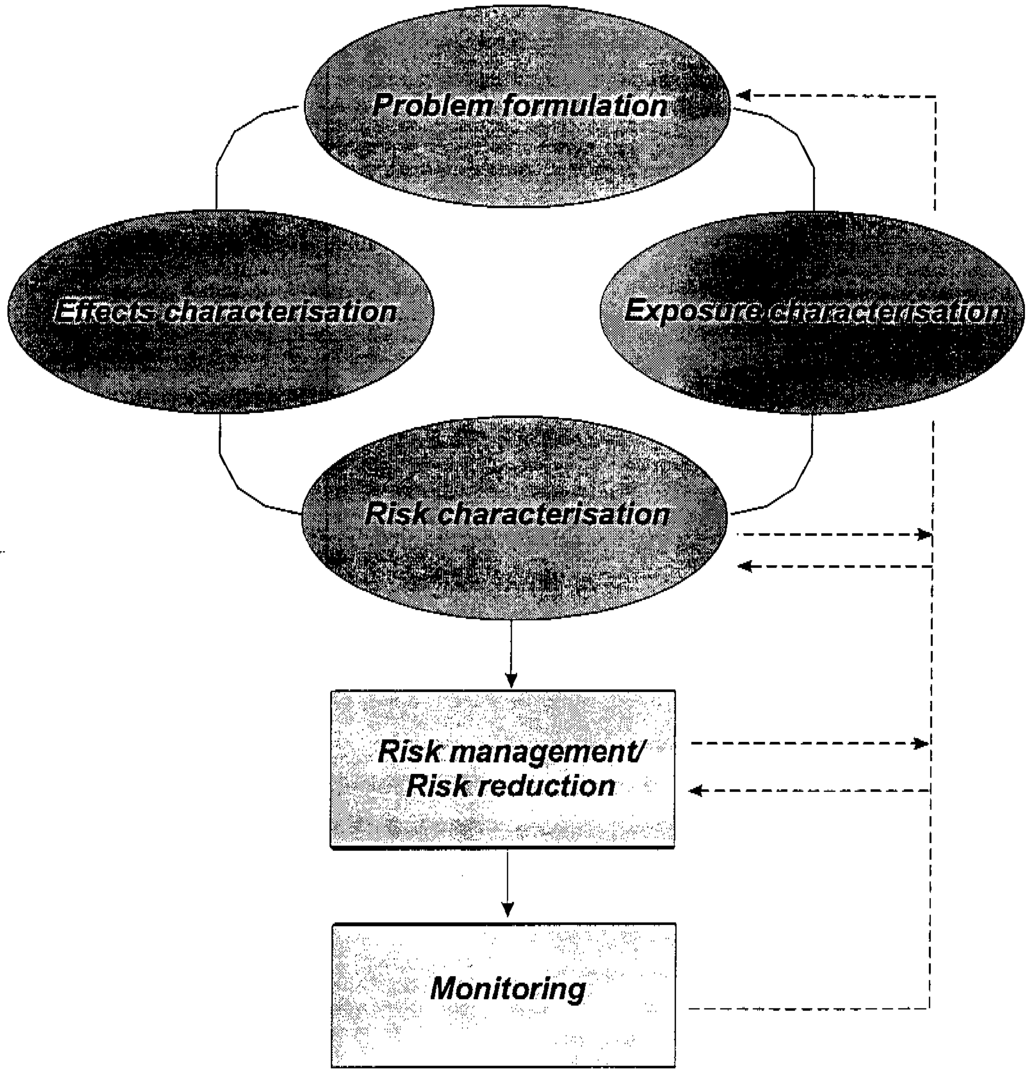

Figure 1 Ecological risk assessment paradigm (modified from van Leeuwen 1995)

Table 1: Definitions of terms commonly used in risk assessment (from van Leeuwen 1995a & US EPA 1998).

Term	Definition
Stressor	Any physical, chemical, or biological entity that can induce an adverse response.
Hazard	The potential, or capacity of a stressor to cause adverse effects on man or the environment, under the conditions of exposure.
Risk	The probability of occurrence of an adverse effect on man or the environment resulting from a given exposure to a stressor.
Risk assessment	A process which involves some or all of the following elements: problem formulation/hazard identification, effects characterisation, exposure characterisation, risk characterisation, risk management and monitoring.
Problem formulation	The identifiaction of the nature of the stressor and the receptor (ie the environment of interest), and the development of a plan for the remainder of the risk assessment based on this information.
Hazard identification	The identification of the adverse effects a stressor has the potential, or capacity to cause (another term for, or confined within, *problem formulation*).
Effects characterisation	The estimation of the relationship between dose, concentration, or level of exposure to a stressor, and the incidence and severity of an effect.
Exposure characterisation	The determination of the emissions, pathways and rates of movement of a stressor and its transformation or degradation in order to estimate the concentration/dose/level to which humans or environmental compartments are, or may be, exposed.
Risk characterisation	The estimation of the incidence and severity of the adverse effects likely to occur in humans or environmental compartments due to actual or predicted exposure to a stressor.
Risk management	A decision-making process that involves considerations of political, social, economic, and engineering information with risk-related information to develop, analyse and compare regulatory options and to select the appropriate regulatory response to a potential health or environmental stressor.
Risk reduction	Implementing measures to protect humans and/or the environment from the risks identified.
Monitoring	The process of repetitive observation for defined purposes of one or more chemical or biological elements according to a pre-arranged schedule over space and time, using comparable and standard methods.

feedback if and when required. Ecological risk assessment can incorporate the assessment of both natural or human-induced stressors, and need not focus exclusively on the effects of chemical contamination, although this area has dominated the research, and is the focus of this discussion. ERA is also sometimes referred to as *environmental* risk assessment (van Leeuwen 1995b), however, this is generally a term given to the broader assessment of hazards to both humans and non-human biota (Suter 1993).

In ecological risk assessment, the biological level to be protected is usually the ecosystem. Essentially, one wants to assess the risks of a particular stressor, for example the potential adverse effects of petroleum hydrocarbons from an oil spill, to the ecosystem of interest, in this case coastal mangrove swamps and estuarine ecosystems. However, it will be impossible to assess the effects on every species as there will most likely be hundreds present. The solution to this, which is discussed in greater detail below, is to select several indicators or endpoints, that best represent the ecosystem of interest. However, the cost is that uncertainty is exacerbated by the fact that many more indicators/endpoints will not have been assessed. Thus uncertainty is increased due to interspecies variation (van Leeuwen 1995a), in addition to that already existing due to stochasiticity (random variation), a lack of knowledge about the stressor, the endpoints being assessed, the ecosystem of interest, and human error (Suter 1993). Thus, it is important to recognise and understand the uncertainties surrounding the scientific information on which the decision will be based (Suter 1993). While past environmental assessment techniques have often incorporated aspects of risk assessment, they have generally lacked a formalised structure, and importantly, have failed to recognise uncertainty. The following section describes, in detail, the process of ecological risk assessment, based on the six steps outlined above.

3 The process of ecological risk assessment

3.1 Problem formulation

Problem formulation is the process of identifying the nature of the stressor and the receptor (ie the environment of interest), and developing a plan for the remainder of the risk assessment based on this information. It defines the objectives and scope of, and provides the foundation for, the entire risk assessment (Pascoe 1993, US EPA 1998). In the case of a chemical stressor, problem formulation would include obtaining and integrating information on the chemical's characteristics (eg properties, known toxicity) and source, what is likely to be affected and how is it likely to be affected, and importantly, what is to be protected. Such information is then used to determine the structure and complexity of the remaining steps of the risk assessment. Problem formulation includes selection of *assessment* and *measurement* endpoints: assessment endpoints are explicit expressions of the actual environmental value(s) to be protected (eg invertebrate community diversity), while measurement endpoints are measurable responses to a stressor that can be correlated with or used to predict changes in the assessment endpoints (eg invertebrate reproduction, macroinvertebrate monitoring) (Solomon et al 1996). It is the measurement endpoints that are directly assessed during the risk assessment (section 3.2). Thus, the selection and use of *ecologically relevant* measurement endpoints is highly important, and is discussed in further detail below (section 3.2).

Once the relevant information has been gathered and the objectives/goals defined, a conceptual model of the problem is developed. This involves defining possible exposure and effect scenarios based on the information. Conceptual models may be represented in the form of flow diagrams describing the possible routes of exposure and potential effects of concern (US EPA 1998). Such diagrams can then be used to develop a series of working hypotheses regarding how the stressor might affect exposed ecosystems and their components (Solomon et al 1996, US EPA 1998). Hypotheses might read as follows: "Atrazine will cause damage to the community structure of macrophytes and reduce the ability of the aquatic habitat to sustain populations of other organisms such as invertebrates and fish" (Solomon et al 1996). The conceptual model is then used to construct an analysis plan (ie the plan for the remainder of the risk assessment). Those hypotheses considered more likely to contribute to risk are targeted (US EPA 1998), and a plan of how to best assess them, using both available and new data, is developed. As with the conceptual model, the analysis plan is often presented as a flow diagram.

The nature of the stressor must be clearly defined (eg the use of a herbicide and its potential toxicity to non-target aquatic organisms and plants in tropical floodplain environments) so as to gain a better understanding of the potential effects, and to assist in the determination of appropriate assessment and measurement endpoints (NLC/***eriss*** 1997). A poorly defined stressor may result in the selection of inappropriate assessment endpoints (and thus measurement endpoints), due to a lack of understanding about the environmental components and processes that will be exposed and potentially affected.

At this point, a distinction between *stressor*, *hazard* and *risk* is useful. To distinguish between the latter two, van Leeuwen (1995a) used the following example: a toxic chemical that is a *hazard* to human health does not constitute a *risk* unless humans are exposed to it. The hazard is the potential adverse effect, while the risk is the probability that it will occur. The stressor then, is the entity possessing the hazardous properties, being the toxic chemical in the above example.

Potential shortcomings in problem formulation that could lead to inappropriate risk assessments include (1) absence of clearly defined goals, (2) endpoints that are ambiguous and difficult to define and measure, and (3) failure to identify important risks (US EPA 1998).

3.2 Effects characterisation

Effects characterisation evaluates the effects of the stressor on the measurement endpoints selected during problem formulation (van Leeuwen 1995, US EPA 1998). As stated above, a good understanding of the stressor will assist in selection of appropriate measurement endpoints on which to assess effects. Therefore, there is a degree of overlap between problem formulation and the initial stages of effects characterisation. Depending on the stressor, effects characterisation can take a variety of forms. In the case of chemical stressors (ie pollutants), ecotoxicological bioassays are usually used to derive concentration-response data for a range of species (see Appendix A for further details on ecotoxicological testing). The results of these bioassays are used to derive an estimate of effect, or 'no effect', and this can be done in a variety of ways. In its simplest form, data from bioassays are used to determine a *predicted no-effect concentration* (PNEC) of a chemical to species of concern (ie relevant aquatic organisms) (van Leeuwen 1995a). The PNEC can be defined as the maximum concentration of a chemical which, on the basis of available knowledge is likely to be tolerated by an organism without producing an adverse effect (Tas & van Leeuwen 1995). Other more comprehensive, and hence complicated, approaches exist, where all the effects data are used to construct a cumulative distribution of known sensitivities (US EPA 1998).

A major attribute of measurement endpoints used for effects characterisation are that they be *ecologically relevant*. Ecological relevance can be described as the ability to directly link the observed response to effects at the population, community and/or ecosystem level (Finlayson et al 1998). This equates to being able to relate the measurement endpoints to the assessment endpoints. For chemical stressors, effects on whole-body responses of individuals (eg growth, reproduction, survival), or on populations or communities are generally considered to possess ecological relevance, while effects below the whole-body level of biological organisation (eg biochemical and physiological biomarkers) are not (Pascoe 1993, Solomon et al 1996).

As stated above, there are a variety of methods that can be employed for effects characterisation. These range from laboratory studies to field surveys, and quantitative assessments to qualitative observations. Laboratory studies allow strict control of all variables bar the one(s) of interest, but they may not reflect responses in the environment. Alternatively, field studies measure biological changes in the actual environment of interest, integrating all the environmental conditions, but as the conditions are not controlled, natural variability may make it difficult to detect the changes. Thus, the choice of method is specific for the type of risk assessment being carried out and its objectives (note that decisions on this are made during problem formulation, well before effects characterisation has commenced).

3.3 Exposure characterisation

Data on the effects of a stressor to an organism, plant, or ecosystem provide little useful information without knowledge on the actual level of exposure. Exposure characterisation estimates the exposure of a stressor to the receptor, by utilising information gathered about its behaviour and extent of occurrence. Such information is usually acquired by the use of historical records, laboratory and/or field experiments, field monitoring, and also modelling.

In the case of a chemical stressor, exposure characterisation requires knowledge about the quantities of, and the means by which a chemical can enter, and subsequently move about within the environment of interest. Processes such as transport, dilution, partitioning, degradation, and transformation (Suter 1993, NLC/***eriss*** 1997), in addition to general chemical properties, and data on rates of chemical input into the environment, need to be considered. In its simplest form, the objective of exposure characterisation of a chemical stressor is to derive a *predicted environmental concentration* (PEC) of the chemical in the environment of interest. This can be obtained in a variety of ways, ranging from estimates based on chemical properties such as water solubility, vapour pressure, fugacity, rate of hydrolysis, photodegradation and microbial degradation, and data on environmental input rates (Macek 1986), to actual measured concentrations in the environment of interest (US EPA 1998). Concentrations can be measured in water, soil, sediment, suspended solids, air, and/or biota, depending on the complexity and objectives of the risk assessment. As with effects characterisation, more complex methods exist for estimating exposure, including cumulative distributions of measured environmental concentrations.

Laboratory experimentation of the fate of a chemical is especially useful when the assessment is predictive (ie the chemical is new, and the environment yet to be exposed). However, such laboratory assessments have the same limitation as laboratory toxicity bioassays, in that the data are not always easy to extrapolate to the situation in the environment. Computer modelling is also used for predicting exposure to chemical stressors (Suter 1993, Nendza & Hermens 1995). The type of modelling that needs to be carried out depends on the type of chemical being assessed, and the environment of interest. This information is first used to form a qualitative or semi-quantitative model, which provides the basis for quantitative mathematical models (van de Meent et al 1995). For ecological risk assessments of aquatic environments, water models, some of which incorporate sediment phases, and multi-media models are used (see Appendix B for examples of some environmental fate models).

For a biological stressor, such as an invasive weed species, exposure characterisation might involve integrating information on the source of the weed, the potential route of entry into the ecosystem of interest, rate of spread, habitat preferences, and reproductive biology.

Effects and exposure characterisation form the overall *analysis* phase of an ecological risk assessment. They are generally inter-related, and thus, usually carried out con-currently and in an iterative fashion: simple assessments are often performed initially, followed by more comprehensive assessments if considered necessary.

3.4 Risk characterisation

Risk characterisation involves comparison of the results of effects characterisation with the results of exposure characterisation, in order to estimate the likely level of adverse ecological effects resulting from the exposure to the stressor (Pascoe 1993, US EPA 1998). There exist a range of techniques for estimating risks, often depending on the type and quality of effects and exposure data. Two of these are described below, regarding the estimation of risks of chemical stressors.

i) PNEC/PEC ratio: The risk quotient

One of the simplest forms of risk characterisation is the calculation of the risk quotient, simply being the ratio of the PNEC to the PEC. It is an indication of the extent to which the highest concentration predicted to cause no effects (PNEC) exceeds (or doesn't exceed) the predicted concentration in the environment (PEC). It is a simple, inexpensive and easily understood means of identifying high or low risk situations that can allow risk management decisions to be made without the need for further assessment (US EPA 1998). Essentially, as the risk quotient increases, the likelihood of adverse effects increases. Above a ratio of 1, environmental concentrations are estimated to exceed effect concentrations, and a risk is deemed to exist. The risk quotient method is often used as the initial component of risk estimation. If there is clearly no risk, and the risk assessor is satisfied with the quality and quantity of data, no further assessment is required. If a risk is perceived to exist, more comprehensive risk estimations can be performed. However, the quotient is not an absolute measure of risk, and thus, may not be of use to a manager who needs to make a decision based on quantified risks (US EPA 1998).

ii) Comparison of cumulative exposure and effects distributions

Exposure distributions, based on measured environmental concentrations, can be compared with effects distributions derived from toxicity values for a range of different species (Solomon et al 1996, US EPA 1998). The degree of overlap of the curves along the x axis (ie the concentration of the chemical in question) indicates the likelihood that a certain percentage of species may be affected. This provides the risk manager with quantified risks for decision-making. In addition, by comparing different exposure scenarios, it is possible to predict the likelihood of effects of different risk management options (US EPA 1998). However, some limitations of this method include the increased data requirements compared to the risk quotient and other methods, and the possibility that the full range of exposure and effects data is not fully covered (Solomon et al 1996, US EPA 1998).

It is important to emphasise that the output of risk characterisation need not be a quantitative estimate of risk. However, sufficient information should, at the very least, be available for appropriate experts to make judgements based on a weight of evidence approach. In the event of insufficient information being available, or uncertainty being judged to be too great, it is possible to proceed with another iteration of one or more phases of the risk assessment process in order to obtain more information and decrease uncertainty (US EPA 1998). Therefore, the whole assessment process is based on a tiered, or iterative process of testing and subsequent assessment, whereby more information is generated based on the previous assessment, in order to decrease the uncertainty surrounding the estimates (figure 2) (Macek 1986; Suter 1993). Regardless of the approach, uncertainty associated with the risk assessment must always be described, while interpretation of the ecological significance of the conclusions must also be carried out (Pascoe 1993, US EPA 1993). In addition, the risks must be sufficiently well defined to support a risk management decision, as discussed below.

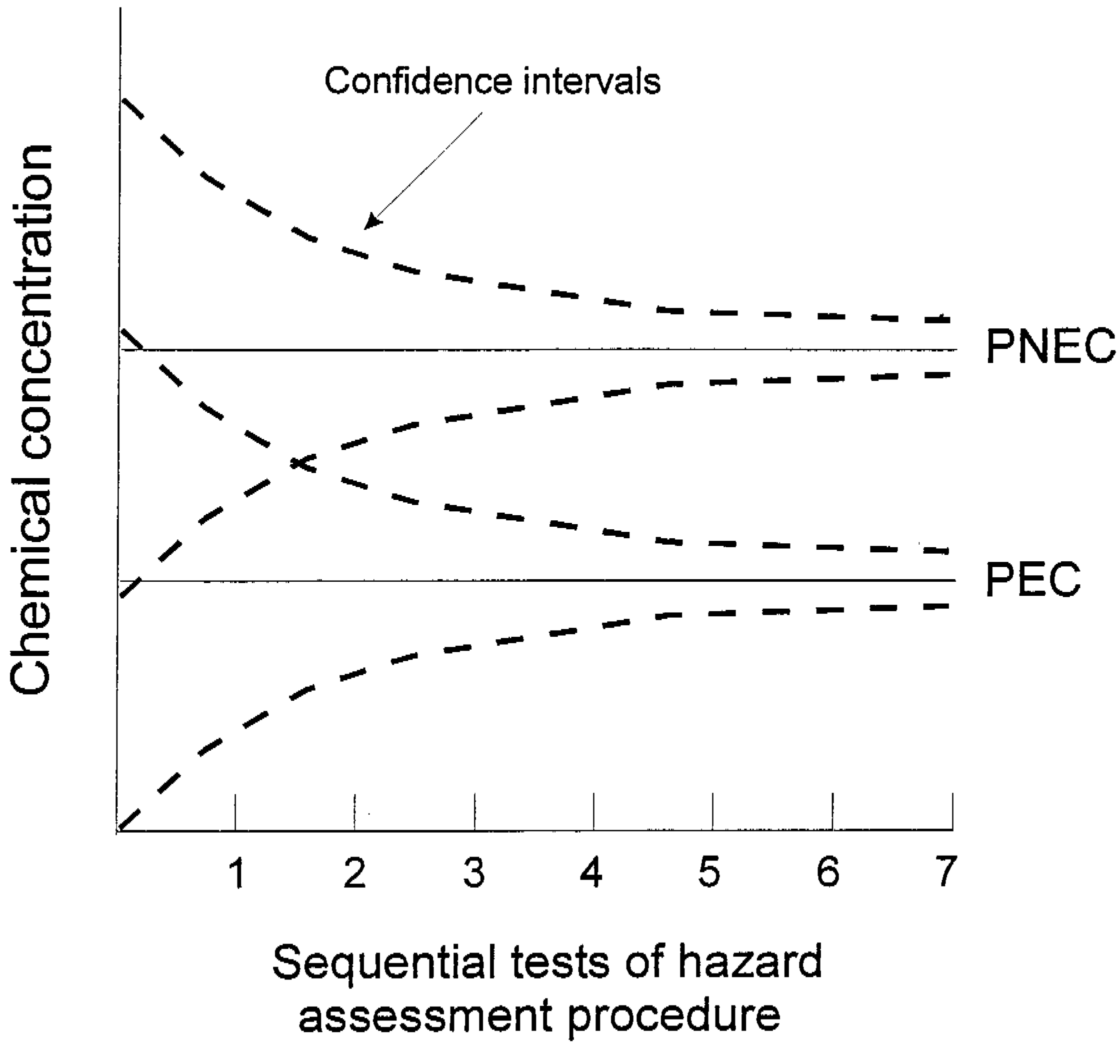

Figure 2 Tiered testing and assessment approach to risk assessment/characterisation (modified from Suter 1993)

3.5 Risk management

Risk management is the final decision-making process that utilises the information obtained from the risk assessment (the processes described above), and attempts to minimise the risks without compromising other societal or community values. According to Vermeire & van der Zandt (1995), the first process of risk management is that of risk evaluation, whereby a decision is made about whether the effects and exposure estimates can be improved by new data (ie the iterative approach to ecological risk assessment), or whether risk management, and subsequently risk reduction, should be implemented. This emphasises the importance of fully describing all uncertainties associated with the risk assessment, during risk characterisation.

It may be that the risks associated with a chemical are minimal, and no risk reduction is required, in which case risk management need go no further. However, it may be that the risks are considered significant, and risk reduction is required. In such a scenario, the results of the risk assessment are not the only factors that risk management considers. It also takes into account political, social, economic and engineering/technical factors, and considers the respective benefits and limitations of each risk-reducing action (van Leeuwen 1995a). It is a multidisciplinary task requiring communication between risk manager, the risk assessor(s), and experts in the other relevant disciplines (US EPA 1998).

Risk reduction involves the implementation of the selected measures to protect the environment from the risks identified. For example, it may be required that a particular industry discharging process effluent into a receiving water install a secondary or tertiary treatment facility. Alternatively, it may simply involve the manufacturer of a chemical to properly label the chemical's hazardous properties and handling requirements, to minimise improper handling/disposal, and therefore, potential adverse effects. Depending on the situation, risk reduction can take a multitude of forms.

Managers must be aware of, and clearly describe in their final risk assessment reports, the sources and causes of risks, the degree of confidence in the risk assessment, the rationale for the risk management decisions(s), and the optiond for reducing risk.

3.6 Monitoring

Monitoring is the last step in the risk assessment process, and one that has largely been ignored as a formal one. The process of monitoring has been explained in detail previously in this course, and is only briefly considered here, in the overall context of risk assessment. Monitoring should be undertaken to verify the effectiveness of the risk management decisions. It should be able to function as a reliable early warning system, detecting the failure or poor performance of risk management decisions prior to serious environmental harm occurring. Therefore, the risk assessment will be of little value if effective monitoring is not undertaken, as its effectiveness will not be evaluated. As with effects characterisation, the choice of endpoints in the monitoring process (ie what will be monitored?) is critical, and should be determined from information gathered throughout the risk assessment. Depending on the nature of the risk assessment and available resources, endpoints may or may not be the same as those used for effects characterisation. However, as 'early warning' may be a key criterion for indicators selected for these monitoring purposes, biochemical and physiological responses (ie biomarkers) may also be applicable.

4 Application to wetlands: Wetland risk assessment

Wetland risk assessment is not a new term or process. The U.S. Environmental Protection Agency (US EPA) defined wetland ecological risk assessment as a quantitative or qualitative evaluation of the actual or potential adverse effects of stresses on a wetland ecosystem (US EPA 1989). In addition, Pascoe (1993) discussed the concept of wetland risk assessment, outlining two case studies to demonstrate its use, while the US EPA (1998) are currently developing *Watershed ecological risk assessment* frameworks similar to that required for wetland risk assessment. Further, the US EPA's recently revised guidelines for *ecological risk assessment* incorporate detailed information on the prediction and assessment of physical and biological stressors as well as chemical stressors (US EPA 1998). They are very broad, and generally embody the concepts of wetland risk assessment that are briefly discussed below.

The general ecological risk assessment paradigm in figure 1 can be applied to the prediction and assessment of risks to wetlands. However, in order for this to be realised, the details within the general structure must be appropriate for assessing the types of change experienced in wetlands. This not only includes recognising the inter-relatedness of the types of ecological change (eg chemical, biological and physical), but the spatial and temporal scales over which they occur. Some examples of methods/procedures that are relevant for risk assessment of wetlands, are described below.

In considering the nature of the stressor and the wetland habitat of interest (ie during problem formulation), it is important to recognise the interactions that occur between habitats and their catchments, in addition to the nature of, and processes occurring within, the habitat of interest. Thus, careful site-specific considerations will be required when defining the objectives of the risk assessment, selecting assessment and measurement endpoints, and developing conceptual models.

Data for effects characterisation should preferably be derived from field studies. Field data are more appropriate for assessments of multiple stressors, a common situation in wetland environments. Depending on the stressor and available resources, such studies can range from quantitative field experiments to qualititative observational studies (Pascoe 1993, US EPA 1998). For chemical stressors, *in situ*, or on-site ecotoxicological bioassays represent a useful approach. However, this does not exclude the use of laboratory experiments if considered useful (eg for single chemicals or when particular environmental conditions need to be controlled). Biological monitoring will most likely also represent a useful method for characterising effects, not only of chemical stressors, but also biological and physical stressors. Sites for assessment can be chosen based on existing information, or from data obtained from exposure characterisation (see below).

For multiple chemical contamination of a wetland, measurement of particular chemical residues throughout the site (perhaps in water, sediment and/or biota, depending on the chemical), based on knowledge of the pollutant source(s) (obtained during problem formulation) would represent an important component of exposure characterisation. Such measurements could be incorporated into a GIS framework, to develop a spatial picture of exposure.

A potentially useful technique for characterising risks in wetlands is via a GIS-based framework, whereby results of exposure and effects characterisation are compared spatially. Relative (semi-quantitative) risks can be determined based on corresponding areas of significant effects and exposure. Additionally, potential problem areas could be identified for further scrutiny. Risk management should be concerned with making decisions on managing inputs into a wetland and/or altering practices associated with the wetland. Again, due to the inter-relatedness of wetland habitats/ecosystems care should be taken that decisions made for one habitat do not have adverse consequences on another linked habitat. Thus, a holistic approach is required. This holistic approach should be carried through the entire wetland risk assessment process, including the monitoring phase, where any adverse on-site and off-site (indirect) effects of the management decisions should be detected prior to further and potentially serious effects occurring.

5 Conclusion

Ecological risk assessment has been used successfully to assess the risks of stressors, particularly chemical contaminants, to aquatic ecosystems for a number of years. Upon identification of a stressor, the objectives, scope, and structure of the risk assessment are determined during an initial step known as problem formulation. Then, by comparing estimates of effects and exposure to a stressor, an indication of the likelihood of adverse effects occurring can be obtained. Such estimates of risk provide another tool for managers to make decisions about the input and potential effects of stressors in the aquatic environment. Part of this process involves the weighting of the estimated risks of the stressor against political, societal and economic factors, to determine their acceptability. If the risk is considered to be unacceptable, risk reduction measures are implemented. The success and effectiveness of the risk assessment and management process is then evaluated by monitoring the environment of concern following implementation of risk reduction. While the process of ecological risk assessment can be applied to wetland threats and issues, it is essential that the large spatial and temporal variability exhibited between wetland habitats be recognised and addressed.

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Appendix A: Ecotoxicological testing for effects characterisation

Ecotoxicology, or specifically, toxicity testing, plays a major role in effects characterisation of chemicals and industrial effluents, and thus is a major component of ecological risk assessment for chemicals. For example, to derive a predicted no-effect concentration (PNEC), one typically measures such properties as acute toxicity to a standard species (for comparative purposes), the relationship between acute and chronic toxicity to a given species, the variability in sensitivity between representative species, and the potential of the chemical to bioconcentrate (Macek 1986). This discussion focuses on the use of ecotoxicology for effects characterisation in aquatic ecosystems.

Ecotoxicology can be simply described as the study of toxic effects on non-human organisms, populations and communties (Suter 1993). The majority of ecotoxicological testing has dealt with effects on the individual organism. This is probably due to mammalian toxicology's prime interest in the individual, as well as the fact that organismal responses are more easily observed and interpreted than those of lower (eg biochemical, cellular) or higher (eg communties, ecosystems) levels (Suter 1993). Some advances have been made in this area, as are described later, but overall, organism-level effects have dominated effects characterisation. Standard single species toxicity tests are generally recommended for use in ecological risk assessment (Suter 1993), however, there is often a need for broader site-specific assessments, based on effects on resident species and local environmental conditions.

A number of decisions need to be made regarding the type of toxicity testing to be carried out, including test species selection, test endpoint selection, and test statistics selection.

Test species selection

When selecting appropriate test species for effects characterisation, several criteria should be considered. The first is whether standard, or local species should be used. The purpose, or objective of the risk assessment should enable a decision on this. Standard species are often used for risk assessments of new chemicals, while local, or regionally relevant species are often used for specific assessments of particular chemicals known or proposed to be released into a particular aquatic ecosystem. For a species to be regionally relevant, it should be an important component of the receiving system of interest. However, a species that has economic relevance (eg fisheries, tourism) may also be a useful test species. Test species should also exhibit relative sensitivity to the pollutant being assessed, and the use of sensitive life stages of a species (usually early life stages) is often employed. Successful and efficient laboratory culturing must also be considered when selecting an appropriate test species. Unfortunately, amenability to laboratory culture often conflicts with the criterion of species sensitivity.

It is essential that organisms representing different trophic levels be utilised. As effects of a chemical on single species will ultimately be extrapolated to estimate risks to communities or ecosystems, testing more organisms will reduce the uncertainty in the estimates. However, as time and resources will often be limited, the general consensus is that an absolute minimum of three organisms from different trophic levels should be tested. For example, a primary producer (eg aquatic macrophyte or alga), an invertebrate (eg cladoceran or copepod), and a vertebrate (eg fish) would represent an adequate range of trophic levels. In addition to the representation of different trophic levels, different environmental compartments should also be represented, depending on the chemical in question. Until recently, most test species have been pelagic, and very little attention has been paid to sediment-dwelling organisms, regardless of the knowledge that many chemicals are known to rapidly adsorb to sediments upon entering the aquatic environment (van Leeuwen 1995b). This point relates back to knowledge of the properties of the chemical, and the environment into which it is, or will potentially be released.

Test endpoints
Having selected appropriate test species, appropriate biological or test endpoints need to be considered. Endpoint selection is based on proper identification of the stressor and its potential effects, and ecological relevance, as discussed in section 3.1 and 3.2 of the main text, respectively.

The choice of endpoint will often also determine the test duration. The majority of acute toxicity tests use lethality as the test endpoint, and generally last for 2 to 4 days. Such an endpoint, although generally less sensitive than most sub-lethal endpoints, clearly indicates an adverse effect at the individual level, and most likely represents an effect at the population level, which is ultimately the extrapolation being drawn from such studies. As such, it can be considered to be ecologically relevant. However, identification of more sensitive, sub-lethal effects on individuals, which can predict, with confidence, effects at the population level, provide a more comprehensive and realistic assessment of risks to aquatic life. Growth, maturation and reproduction are commonly assessed sub-lethal endpoints, with the latter often, but not always being the most reliable indicator of adverse effects in the environment. For particular organisms, chronic toxicity tests can be carried out in relatively short time periods. For example, algal bioassays can generally assess pollutant effects on ecologically relevant endpoints such as population growth over approximately 72 h (3 days), while similar endpoints can be assessed using *Hydra*, over 96 h (4 days).

Recently, more subtle endpoints have been investigated for potential use in ecotoxicology. These include the use of biomarkers such as the mixed function oxidases (MFOs), or cytochrome *P*-450s, and immunotoxicological endpoints. MFOs have the disadvantage that while they may be suitable indicators of pollutant exposure, they are difficult to relate to adverse effects, or toxicity. As a result, they cannot be considered ecologically relevant, and hence should not be used as endpoints for effects characterisation.

Test statistics
There are two major approaches to statistics for ecotoxicological testing; 1) hypothesis testing, and 2) point estimation, and there is currently considerable debate over which is more appropriate.

Hypothesis testing is primarily concerned with comparing a series of two or more concentrations, typically serial dilutions, to control conditions (ie absence of the pollutant). Generally, such tests identify the highest concentration of a dilution series that does not differ significantly from the control condition, known as the no-observed-effect concentration (NOEC) (Chapman et al 1996). It should be noted that hypothesis testing need not be restricted to the estimation of the NOEC alone, but it is generally the most common statistical estimate (Chapman et al 1996), and the one that is used to estimate the PNEC. The major advantages of hypothesis testing for effects assessment are that it is a well suited technique for comparing a control treatment with a particular concentration of pollutant, and the statistical computations involved are well known and generally straight-forward. In addition, the past reliance on hypothesis testing makes it easier to directly compare present studies with previous research if hypothesis testing is utilised. The major disadvantage of hypothesis testing, is that the calculation of the major statistical estimates, the NOEC and LOEC (lowest-observed-effect concentration) can only be concentrations used in the experiment. As experiments are often conducted using serial dilutions (eg 0.1, 1, 10 and 100 mg/L), there are significant concentration gaps for which the effects are unknown, although they will generally not be greater than an order of magnitude in size.

Point estimation estimates the concentration associated with a specified level of change from that observed under control conditions, generally known as the effective concentration (EC) (Chapman et al 1996). It allows the estimation of concentrations that would cause different magnitudes of responses, such as a 50% reduction in growth (EC50), or a 10% reduction in reproduction (EC10). The effective concentration can also be referred to as the lethal concentration (LC) when lethality is the endpoint. The major advantage of point estimation for interpreting ecotoxicological data stems from the above-mentioned disadvantage of hypothesis testing. Point estimation uses regression techniques to quantify the response of organisms at every concentration by determining a concentration-response relationship and estimating where effects of a particular magnitude will occur. As a result, ECs are not restricted to being one of the test concentrations, as they are estimated from the concentration-response curve that is fitted to the data (Chapman et al 1996). In addition, different levels of effect can be estimated (eg EC1, or EC50) depending on the objective of the assessment, or what is considered biologically or ecologically significant. For example, the concentration of a pollutant in a water body could be considered to pose no risk if it does not exceed the estimated concentration that has an adverse effect on 1% of the tested organisms (ie EC1). For point estimation, the EC1 could be considered the PNEC, although other regression techniques have been developed to derive statistical estimates analagous to the NOEC (eg BEC10; Hoekstra & van Ewijk 1993).

While hypothesis testing has dominated statistics in ecotoxicology, there is a strengthening viewpoint that point estimation techniques are more suitable for use in ecological risk assessment. This is mostly due to the advantages described above.

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Appendix B: Examples of environmental fate models for exposure characterisation

Some examples of environmental fate models used for exposure characterisation are described below. For further details the reader is directed to the review of van de Meent et al (1995).

Water models

Dilution models

Dilution models divide the concentration of a chemical in a pollutant mixture by a specific stream dilution factor (DF). The DF is usually based on measured volumes and flows of both the chemical discharge and the river/stream. Obviously, this is only the first step in understanding exposure, but it does provide an estimate of the concentration of the chemical in the aquatic environment prior to processes other than dilution acting upon it. In addition, such models can apparently give satisfactory predictions of exposure within a few kilometres from the discharge point, as dilution will be the major factor acting upon a chemical within this zone (van de Meent et al 1995).

Dispersion models

Dispersion models are used to describe the concentration profiles of chemicals throughout the water column, taking into account natural factors such as turbulence and even tidal movements. They are often used to model the extent of chemical dispersion following a spill, or even to monitor pollutant plumes such as produced formation waters or drilling muds from oil platform. They are only of real benefit where a point source of a chemical or discharge exists.

Compartment models

Compartment models describe the transfer and transformation of chemicals through a surface water system. Most water-based compartment models contain a water and a sediment layer. These models are somewhat more complex than the previous two, and therefore require the input of more informtation (eg on biodegradation, photolysis, volatilization, sorption).

Multimedia models

Multimedia models incorporate several compartments (eg water, aquatic biota, sediment, suspended solids, soil and air) and are utilised in situations where chemicals are known to be released into several compartments simultaneously, or when a chemical is thought or known to move between several compartments, and those compartments are of interest to the risk assessment. As they are more complex than the models described previously, more information is required. Information on the chemical includes molecular weight, solubility, LogK_{OW}, vapour pressure, and its biodegradability, while half lives in the various compartments is also useful, but not a necessity.

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Community involvement in wetland management: Lower Mary River Landcare Group

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Clair O'Brien has been President of the Lower Mary River Landcare Group since early 1994, and coordinator of the Group since 1996. Her family own and operate 'Carmor Plains', a Brahman stud property on coastal wetlands between the Wildman River and Mary River in the Northern Territory.

1 Introduction

I've been in the Northern Territory for four years and I have a background in primary production. Our livelihood depends on the land and what we do with it.

We came here to the NT after we had several properties in Queensland. I was born and bred on cane farms, then moved onto cattle properties after I was married. We had 10 years of drought in Queensland before we moved over here. Everyone said "Why did you move?" But we'd spent 30 years building the property up from nothing, right up to the point where my husband said there was nothing left to do but build me a house so we'd better go!

As a family, coming out of 10 years of drought in Queensland, we've been through the process of a Property Business Plan. Our Mission Statement is 'We want quality cattle, depth of purity, and quality country'. We'd put our Queensland property on the market in 1990 in order to come to Katherine, but no one made a bid. Later when we saw Carmor Plains and wanted it, we got a buyer almost immediately. We still had grass on our Queensland property after 10 years of drought.

So we moved 2500 head of stud farming cattle and a family of four generations to the Northern Territory, which was quite a move. When we started at Carmor Plains we were thrown in the deep end, as working on and with the wetlands was a new experience. The Wet is our drought, our worst time of year. Carmor Plains has 100 000 acres (41 000 ha), 60 000 acres of which is floodplain adjacent to the Mary River catchment area (map 1). We share a boundary with Kakadu National Park and the Wildman River. We are fortunate to have very little Mimosa pigra weed on Carmor Plains, but it's a constant job to monitor Mimosa and make sure it doesn't explode.

With the wetlands, we're learning all the time. In the 4 years we've been at Carmor, we've really noticed how the country is coming back. We've lightly stocked the property and the improvement has been phenomenal. As 60 000 acres are under water for 3–4 months a year, we can't have cattle out there, so we leave them on the high country. When they do go back out on the floodplains, it's prime feed. So we're really only using half of the property and I guess that's where we're fortunate with an equal break-up of the country. Some of the other Mary River catchment properties don't have the ability to hold cattle on their high country. Some properties only heavily stock during the Dry, then sell for the export market.

We were also surprised to find out about the proposed Mary River National Park when we came here. All the documents said 'the Park' but 'the Park' was all the privately owned areas around. We had just bought into it. We said "we're not the Park!" and started finding out more about it.

2 Lower Mary River Landcare Group

While trying to find out what was really going on, I became involved in the Lower Mary River Landcare Group (LMRLG) and took over its presidency. My involvement has grown and grown since. Trying to find out what government departments are doing is quite difficult at times from a lay-person's point of view. Having the time to do it is also a problem. We only manage it because of our family structure on the property. My husband, his bachelor brother, our eldest son and our youngest daughter live at home, and Carmor Plains is a totally family-run operation. The Landcare Group got us involved in the community.

The LMRLG brings the whole community in that area together to address land management issues. 99% of the landowners of the area are members of our Group, apart from a few members in the upper catchment who are waiting to come on board. The diversity of members in the Mary River catchment area is quite unique. There are graziers of buffalo and cattle, tourist operators (eg boat tour operators and wilderness lodges), gold and sand mining companies. The area also includes the Mary River Ranger station which manages ten reserves they hope eventually to amalgamate into the proposed Mary River National Park. There is a cashew farm with a proposed horticultural area and the Mount Bundey Defence training area. It's a very diverse group, and to have them all in one room talking about Landcare and management ethics is an experience! It certainly leads to an appreciation of other people's perspectives and you learn to make compromises. Landcare has made people in our area much more aware of their actions. They still might go ahead and do something, but they begin to think about its effects on other people.

Members currently pay an annual fee each year. To be a full member of the Landcare Group you must own land or a concession in the area. Full members have full voting rights and hold positions on the committee. Associate members are just interested people, able to have their say but without a vote. The Group's constitution states that landholders will run the committee.

There hasn't been a lot of Aboriginal involvement in the LMRLG to date, as there are very few Aboriginal people living in the catchment. However now the Group has expanded to include the entire catchment, Jawoyn land owners may be involved. The rangers based at South Alligator in Kakadu National Park have always been associate members of the LMRLG, and may come on as full members now that the LMRLG area has been extended to include the total Mary River catchment.

3 Funding for the Group

The funding that our Landcare Group receives is very minor and includes membership fees and landholder contributions. As part of landholders' own land management they do saltwater intrusion works, wildfire and erosion controls on an ongoing basis, putting money into it all the time. Other groups like the Centralian Land Management Association get a lot of funding eg to employ people for rabbit control. Our own area consists of individual landholders doing individual property management. Their yearly budget for Landcare works would include:

- $20 000 (very conservative figure) for salt water intrusion
- $50 000 for wildfire control
- $15 000 for erosion works
- $10 000 for feral animals control
- $20 000 for conservation
- $40 000 for water quality monitoring
- $250 000 for weed control, with government subsidies for aerial control and poisons on big infestations of *Mimosa pigra*.

These are the baseline figures for landholder contributions to fuding, based on an average of 10 properties.

The only government funding the Group receives is for the coordinator, to produce the newsletter and keep abreast of what's going on. The coordinator position is important because it helps keep everyone informed. There have been suggestions that landholders and other users of the Mary River area, including tourists, could be charged a levy to contribute to the LMRLG coordinator costs, allowing the group to do even more while not just relying upon government funding.

4 Group coordinator

For the past 12 months I have been a paid Landcare coordinator for the LMRLG, which has made life more hectic but a little easier financially. I've kept on doing the work I was doing but I'm getting paid for it and have a vehicle to use. I produce a newsletter every 2 months for the group with the assistance of my family at home. The newsletter has got better and better! We've come a long way since the first edition, with a broader scope of articles.

As coordinator, I also set up a communication network. The coordinator is the centre point, surrounded by Landcare members, then an inner circle of institutions and government/businesses eg the media, NT Bushfires Council, Parks Australia North and eriss (figure 1). I have a contact name and number for them all. It is quite involved but it's all about keeping the Landcare Group informed. We hope funding for the Landcare coordinator position will continue next year.

5 Coordinating major issues

There is a coordinated approach within the Landcare Group to major issues. For example, the Group has agreed to clearing guidelines and accepted them. We don't then go around reinforcing those guidelines, we just hope the landholders follow them. We find that in a lot of cases they do. They take on those issues, weigh them up and then you find that they may still go ahead, but they have probably made a compromise somewhere.

The issues that united the Group when it began in 1989 were saltwater intrusion, land degradation (including Mimosa pigra and other woody weeds), feral animals, wildfire and the value of natural flora and fauna resources. These issues become very complex at times with such a diverse group, but we work through them. The Landcare meetings are a forum through which you can just thrash those issues out.

At the last meeting we had, the Parks & Wildlife Commission of the Northern Territory had written to the LMRLG, asking us to comment upon a recent proposal by two boat operators who were also LMRLG members. The members currently operate two 25 passenger capacity boats at the Rockhole on the Mary River. One of them proposed to use a larger boat, carrying 50 passengers. The second operator had offered to take the smaller boat, which would result in two small boats operating in one area while the big boat went somewhere else because it couldn't access places the smaller boats could. It actually took pressure off the areas visited, with the added advantage that tourists didn't see other boats nearby, thereby helping to keep the Mary as a more 'isolated' experience.

When we talked about it as a Landcare Group, we said that we didn't want to be the ones to make a decision on that, but we wanted assurance that no bank erosion would result from the larger boat's wake or damage to the bank by people's feet. We used this issue as a lever, saying that we hoped this sort of issue would be dealt with through a management committee for the proposed Mary River National Park, upon which there would be a LMRLG representative.

As the Mary River is so close to Darwin we got a lot of pressure from government departments, with government officers coming out to have a look around, telling us this version or that version and then going away. We got many conflicting reports from the Department of Primary Industry & Fisheries, conservationists and others. The graziers are lay people; they don't know who to believe. Their lease documents say they're allowed to graze cows, so why are they told they should run their property like a national park? It is conflicting, putting members in quite a quandary.

So the LMRLG said there should be a coordinated approach, and the Minister set up the Mary River Technical Working Group to coordinate all the government bodies that come out to work in the Mary River area. The big wetlands conference that met in Darwin in 1995 resulted in the formation of a Wetlands Taskforce who are supplied information by the Technical Working Group. The Wetlands Taskforce has been developing the first integrated catchment management plan for the NT. I am the LMRLG representative on the Taskforce, along with others representing the amateur fishermen, the tourism industry and the graziers. An independent chairman is flown up from Victoria for every meeting. We've worked on the plan for 18 months now, overcoming little problems along the way. At grassroots level we want the integrated catchment management plan to be a working document and not gathering dust on shelves. The plan is currently awaiting ministerial approval before it is released for public comment.

6 Involving landholders in research

Funding agencies are placing more emphasis on communication between the researcher and landholders. Researchers should involve local landholders in the development of the program, the research and the outcomes. As a landholder, my advice is that you talk to us!

I sit on a lot of research assessment panels and we go through the documents and they say they've consulted with the LMRLG and yet we've never seen them!

A good way to contact landholders in the Mary River area is to contact the LMRLG first. We welcome people to visit, with prior consent, because we don't know what we've got or what you're looking for. We are lay people and know things from the practical level, but from the research, technical or scientific side we don't know how to mesh in with you.

However, we do live out there and see things that could be researched, so we can offer ideas for research priorities. For example, at Carmor Plains we don't burn the vegetation. Visitors can see the difference along our boundary with Kakadu National Park, which is burnt annually. There is a marked difference and it should be researched. We want to show the world that we can run an ecologically sustainable property, with people and cattle, yet maintaining the biodiversity of animals and birdlife. How do we document that, to justify what we are doing? We think there should be something done but we'd need some help on how to start.

Another issue is the planting of introduced grasses as improved pasture species. There's been a lot of talk about growing Para grass eg taking out Mimosa by chaining and then planting Para grass in its place. Although this is not common practice, it is happening because there's no alternative. Para grass chokes out the young Mimosa coming back up, giving the desired result with less chemicals and expense. This way the landholder can generate income from previously unproductive land, recovering that dollar that they're spending in weed control. To do control works to make the country viable, you must get the dollar out of those animals and improved pasture is the way to do it. The best option from an environmental perspective would be to plant native grass species instead of Para grass, but seed is difficult to get and has very low gemination. Marrakai Station are harvesting native grasses, but viability and quantity of seed is still a problem. More research is needed.

I appreciate the opportunity to be involved in this course. As landholders within the LMRLG we are there at all times to be contacted, and we hope to be of further assistance to researchers. We look forward to strengthening communication links with regular sessions like this one.

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Map 1. Mary River locality.

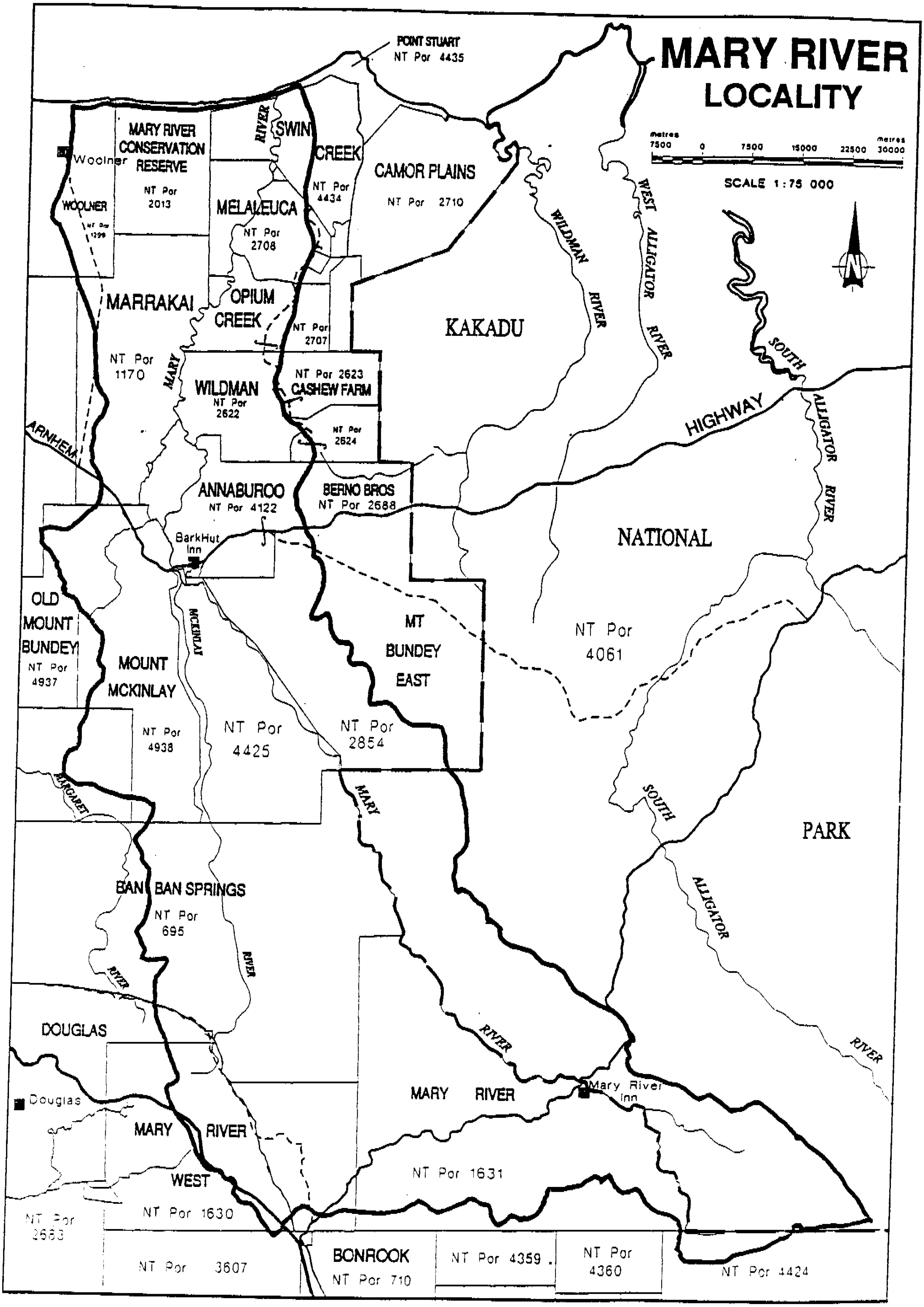
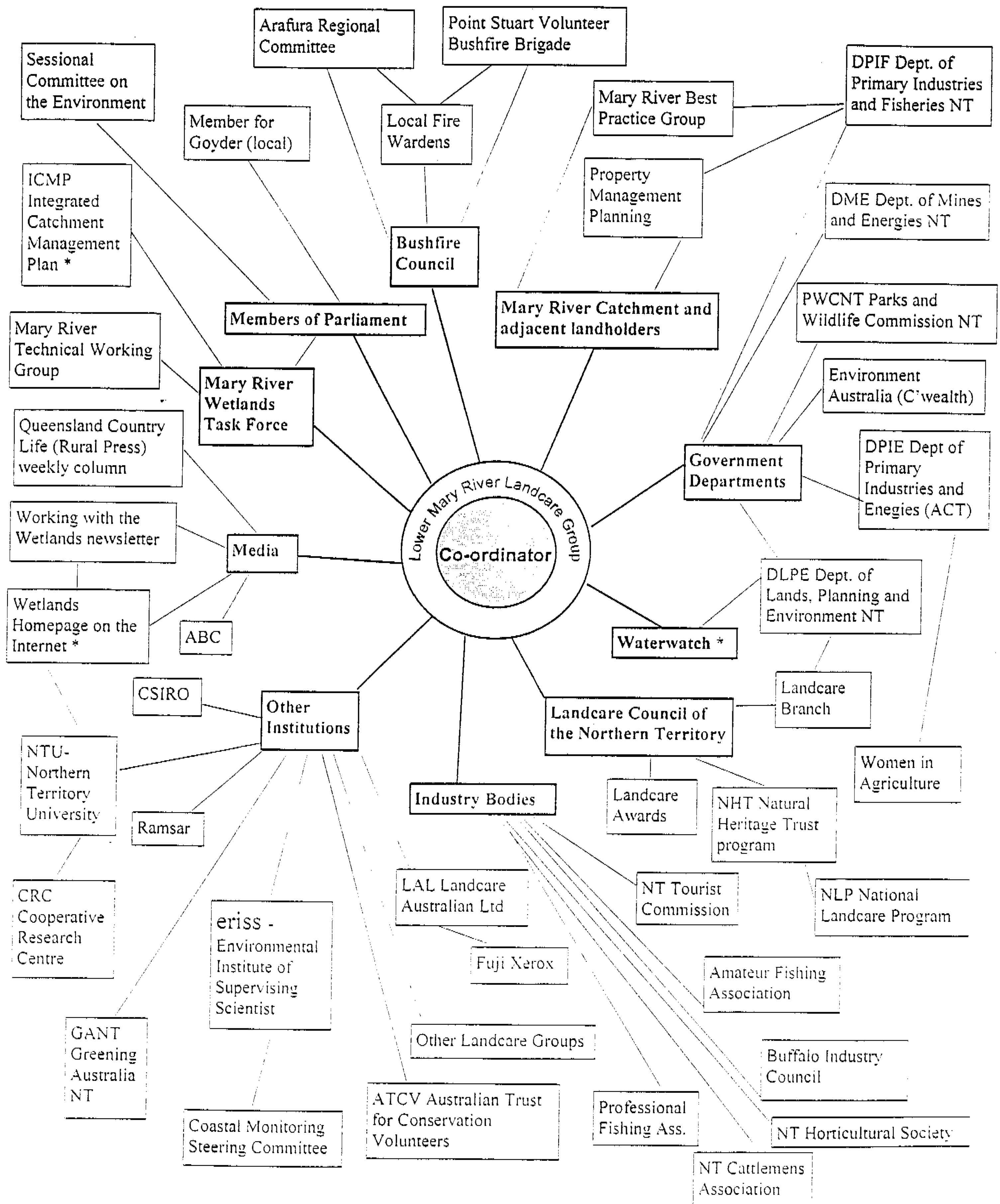


Figure 1. Communication Network Plan for the Coordinator of the Lower Mary River Landcare Group.



*In process but yet to be implemented.

Community involvement in the management of our waterways: NT Waterwatch

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Abstract

State and federal governments in Australia have recognised the need to involve the community in management of waterways, as it helps to build community awareness of water quality issues, and fosters a sense of 'ownership' of local waterways and catchment management initiatives. Waterwatch is an Australia-wide, community-based program which fosters cooperation between government agencies and communities. Volunteers carry out water quality monitoring and other on-ground activities in their local catchment, assisted by coördinators. In the Northern Territory, Waterwatch activities are coordinated by the NT Waterwatch facilitator. Volunteers from both urban and remote areas enthusiastically participate in water quality monitoring, while taking into consideration special factors arising from the remoteness and tropical climate of much of the Northern Territory.

Keywords: Waterwatch, community involvement, water quality, monitoring

1 Introduction

Waterwatch is an Australia-wide program that involves volunteer water quality monitoring and on ground activities that focus on the ecological sustainable management of our waterways. An important component of Waterwatch is facilitating communication between waterway stakeholders (government departments, researchers and landholders) to address issues of water resource management. In particular, Waterwatch recognises that the community is a vital contributor to waterway management and, by providing the necessary training and management tools, makes this possible. Even ten years ago, much of this communication and information exchange did not occur. If it did, it was often in the form of government directives to the community, with community consultation and involvement at a minimum. This is where community-based catchment management programs like Waterwatch and Landcare have made an important contribution to integrated catchment management. In many instances, the Waterwatch program has helped to bridge this communication gap between the community groups and scientists. Through community-based water quality monitoring activities, Waterwatch has leveled the water resource management 'playing field' by giving the community the tools to access and contribute to waterway management decision making.

2 Waterwatch: a national network

Waterwatch is a national volunteer monitoring and environmental education program aimed at raising awareness of water quality issues and involving the community in action for healthy, sustainable waterways. The Waterwatch program was announced in 1992 as an Australian Federal Government initiative in response to a growing number of community groups requesting involvement in assessing and managing water quality issues in their local creeks, rivers and wetlands. Interestingly, the announcement coincided with a range of federal and state government initiatives which heralded the recognition by government bureaucrats that ecological sustainability could only be achieved through raised community awareness and involvement in natural resource management decision making (Phillips 1997).

Today, the Waterwatch program is a network of more than 50 000 people, regularly monitoring close to 4000 sites around Australia. For those involved in Waterwatch, the value of the network is that it operates as a conduit for information exchange, sharing of resources and allows for the development of a consistent approach. However, there are still many bureaucrats and academics who have a tokenistic approach to community involvement in natural resource management, or who see it as a threat rather than an opportunity. These people soon discover that trying to undermine the work of a Waterwatch group, which is part of such a strong national network, is not worth their while. They only need to read the range of contributions made to water resource management by the 'Waterwatchers' featured as case studies in Waterwatch Australia's *Snapshot 97* publication (Waterwatch Australia 1997) to realise that this national program has the 'runs on the board'.

A number of facilitators and coordinators are in place to maintain the strength of the network and provide necessary support to enable community groups to be involved in Waterwatch. The National Waterwatch Facilitator, a position based with Environment Australia, provides the national administrative direction for the Waterwatch network. Through a partnership agreement with the federal government, each state/territory water resource authority implements a Waterwatch program. The state/territory facilitators meet twice a year as the Waterwatch Australia Steering Committee to address issues associated with implementing the Waterwatch Australia Strategic Plan. Each state/territory Waterwatch Facilitator has a steering committee of community and government representatives to oversee the development of their strategic plan. In the Northern Territory, the NT Waterwatch Facilitator is employed by the Water Resources Division of the Department of Lands, Planning and the Environment (DLPE). Operating funding for facilitating the implementation of the Northern Territory program has been provided to date by the federal government under Natural Heritage Trust (NHT) funding.

The Regional or Catchment Coordinator plays a vital support role for the Waterwatch groups who monitor waterways and conduct awareness activities for healthy waterways. These coordinators are people from the local community who are funded through the NHT initiative to coordinate Waterwatch in their local catchment area or region. Training for the Coordinators – in the aims of Waterwatch, water quality monitoring, data management and group coordination – is arranged by their state/territory facilitator. In the Northern Territory, NHT funding for these coordinators is hosted by non-government organisations such as Greening Australia, Keep Australia Beautiful Council, the Arid Lands Environment Centre and Dhimurru Land Management Corporation.

Interested community groups are inducted into the Waterwatch network and are provided with necessary support. Waterwatch participants and coordinators can exchange catchment information and share water monitoring experiences across catchments and even across state/territory boundaries (Anon a,b,c; Waterwatch Australia 1997). Moreover, the Coordinators assist groups to liaise with the relevant government authorities and catchment stakeholders. Through these contacts, groups can gather catchment information to build a picture of the health of their catchment and to contribute their waterway data to natural resource management decision making forums.

Although the Waterwatch Australia network is designed to service national needs, it does have global partnership links to similar initiatives such as the Globe program and the United States' Riverwatch network. Last year, the Malaysian government liaised with the National Waterwatch Facilitator to adopt the Waterwatch Australia model for their country. The Malaysian Waterwatch program will have an emphasis on groundwater monitoring and will draw on the techniques used by South Australia Waterwatch.

3 Community involvement

3.1 Local monitoring and data management

Although Waterwatch Australia operates under a national Strategic Plan and complementary State/Territory Strategic Plans, there is scope within the national framework for Waterwatch groups to evolve within the network to meet their own needs and interests. Waterwatch Coordinators and Facilitators tailor Waterwatch to meet community needs rather than dictate a set of hard and fast rules for every participant. If, for example, a group decides that their involvement is in collecting data to produce a water quality report for the local catchment committee, then the level of confidence in the data collected would need to be high. In formulating such a monitoring program, the coordinator would advise on a rigorous monitoring program and arrange the necessary training. This would incorporate regular sampling, strategic site selection, quality assurance/control and reliable monitoring equipment. At the other end of the Waterwatch participation spectrum, a group (eg school class) may only be interested in monitoring a site with more of a focus on providing students with an understanding of monitoring equipment or an aquatic biology lesson.

Through an equipment sub-committee of the Waterwatch Australia Steering committee, a 'clearing house' has been established to review water quality equipment that comes onto the market. New equipment is checked for its suitability for community use by assessing characteristics such as cost effectiveness and ease of use (including calibration, time and field use). As an example of the equipment used, NT Waterwatch groups generally use a test kit for dissolved oxygen measurement that takes just 10 minutes for a volunteer to add three tablets and to do a small titration to get a mg/L measurement. Such kits are easy for community groups to use and produce reliable results. To enlist local support for Waterwatch, community groups are encouraged to seek local sponsorship to purchase their kits.

Another piece of practical Waterwatch equipment is the turbidity tube. This perspex tube with turbidity levels etched into the side requires groups to collect a water sample and put it into the tube until the white backed Waterwatch logo at the bottom of the tube can no longer be seen. By reading off the water level against the scale, Waterwatchers can record the turbidity level, using a piece of equipment that costs just $50. Besides dissolved oxygen and turbidity, groups can test for a range of biological and chemical parameters. These include pH, temperature, salinity, dissolved solids, phosphates, nitrates and faecal coliforms. Waterwatch groups also assess the health of their waterway by sampling macroinvertebrates and monitoring riparian and instream vegetation. The *NT Waterwatch Guide to Macroinvertebrates*, produced in consultation with the scientists from the national Monitoring River Health program, allows groups to record a measure of water quality from the number and variety of macroinvertebrates found (NT Waterwatch n.d.).

Any meaningful data collection project needs to have a means of managing the data from storage to data manipulation to reporting. To assist Waterwatch groups with this, Waterwatch Australia launched a national Waterwatch data base in 1997. All Regional and Catchment

Waterwatch coordinators participated in a 1 day training course to equip them with the skills to coordinate data management in their area of operation. This data management tool allows groups to develop graphs and produce short reports about their data. The stand alone Waterwatch Data Entry program allows the groups to store their data with the option of uploading it into the Database for catchment reporting.

3.2 Waterwatch events

In addition to the monitoring described above, Waterwatch Australia encourages groups to be involved in a range of international (World Wetlands Day, World Environment Day), national (Water Week) and community events to communicate information about their activities. This helps to increase local community awareness of waterway management issues and exposes Waterwatch to the broader community. In national Water Week, the Waterwatch network coordinates a national Snapshot of water quality. This involves a national macroinvertebrate or turbidity sampling event. In 1997, over 50 000 people participated and, with the considerable media coverage, celebrated community involvement in waterway management. Other groups, such as those in Darwin, organise and participate in an annual Waterwatch community drain stencilling event to label drains with a message 'This Drains to Our Creek'.

4 NT Waterwatch: from facilitator to community action

Waterwatch has been underway in the Northern Territory since 1994. As discussed above, the NT Waterwatch Facilitator is based in Darwin in the Water Resources Division of DLPE. In 1996, the Facilitator, together with a Water Advisory Committee, produced the document *Strategic Plan for NT Waterwatch for 1997–2000* (DLPE & WAC 1996). The Plan identifies some of the challenges faced by NT Waterwatch and lists objectives for the program which will be reported each financial year. In 1997, the Minister for Lands, Planning and the Environment appointed the NT Waterwatch Steering Committee which has statutory reporting obligations under the NT Water Act. This committee consists of natural resource management and community representatives and will provide an advisory role to the NT Waterwatch Facilitator.

With the indigenous demographics of the NT, it is important that Waterwatch as a community involvement program be accessible for the natural resource management issues of indigenous communities. Use of Traditional Ecological Knowledge in monitoring the health of waterways is an avenue that needs further Waterwatch attention. For guidance on meeting indigenous communities needs, the NT Waterwatch Steering Committee has a representative from the Northern Land Council and the Central Land Council.

Due to program resource limitations, the NT Waterwatch participants have been utilising Queensland's Waterwatch manual to date. In 1998, the Waterwatch Australia Steering Committee will release a shell for a national Waterwatch manual that will build on existing state Waterwatch manuals and will be designed to include state/territory supplements about the water resources, surface water and groundwater. For example, in the Top End of the NT, the water temperatures are usually 30–35°C with some natural hot springs reaching 40°C. These levels are not represented in the Waterwatch manuals to date and will need to be included in the national manual, as they will service the needs of the Wet-Dry tropics as well as groups in Australia sampling in areas experiencing thermal pollution. Also NT Waterwatch, through the appointment of a Coordinator for Alice Springs, will have the opportunity to adapt South Australian groundwater Watertablewatch for use in the NT.

In the NT, Regional Waterwatch Coordinators currently provide support to groups monitoring 55 sites in:

- Darwin
- Litchfield Shire
- North East Arnhem Land
- Alice Springs
- Katherine
- Mary River.

4.1 Darwin Waterwatch

In Darwin for example, groups have been monitoring 16 sites along Rapid Creek, which is 9.5 km in length and flows through Darwin city. The 16 sites are monitored monthly by a range of adult Landcare and school groups and the data entered into the Waterwatch Australia Database. In 1998, the Regional Coordinator intends to produce a water quality report which will be provided in draft form to the DLPE water quality scientists for technical comment prior to final release.

Waterwatchers are encouraged to take local action should they find an issue. In Darwin for example, pollution spills have been reported as a result of monitoring by Waterwatch volunteers. For one spill, the Darwin regional coordinator was sampling in a creek, noticed high nitrate levels and a sewage smell and reported it to the NT government's pollution response line. Further investigations by authorities found that the source of the sewage pollution was a failing sewage pump. Similarly, spills have been reported in the Duke Street waterway in Darwin where there are numerous car yards in the catchment. This site is being monitored by Waterwatchers and a photographic record being kept of the oil and rubbish. The Waterwatchers hope to put pressure on the local government authorities to take legislative action on the offenders to help clean the area up.

4.2 Nhulunbuy Waterwatch

In Nhulunbuy, the Regional Coordinator has had the task of developing a local Waterwatch program in partnership with Nabalco mine, the local Aboriginal people (Yolngu) and other residents. The Coordinator has received considerable sponsorship from Nabalco mine that has enabled her to purchased a Horiba multi-probe monitoring kit that she regularly calibrates. Training in calibration procedures has been provided by the Nabalco laboratory staff and the DLPE water quality scientists. As a recognition of the importance of embracing the local Yolngu people, the Coordinator asked for a Yolngu name for their Waterwatch group. They have been given the name Gapuwu Mel'ngu Mala which translates to 'Water for Surveillance People'. Raymattja, a leading Aboriginal woman, has put an indigenous perspective on the value of caring for the riparian vegetation around the local lagoon by conducting bush tucker walks with local school children.

With assistance from Department of Primary Industries Weeds Education Officer, the Coordinator has implemented an education program to train local people in identifying and reporting the aquatic weed *Salvinia molesta*. In addition, the Coordinator is working with the Yirrkala school to develop a local Waterwatch logo that features a Yolngu drawing of a water monitor in a traditional Aboriginal artwork design. For the Gapuwu Mel'ngu Mala group, monitoring takes on an additional safety concern not experienced by our southern colleagues.

This hazard is crocodiles and is a major hindrance to regular sampling. As a safety precaution, the local Parks and Wildlife staff are invited to talk to Waterwatch groups about crocodile awareness and safety techniques. The Nhulunbuy coordinator has also written a crocodile safety pamphlet for the Waterwatchers.

4.3 Litchfield Waterwatch

In the Litchfield Shire, the Coordinator has focused on raising awareness about wetland issues associated with the many lagoons in the Shire. Landcare field days have included macroinvertebrate and habitat monitoring to raise awareness about the unique wetland habitats the rural residents have in their backyards. The Litchfield Waterwatch Coordinator and the DLPE Landcare officer have cooperated to produce community newsletters that raise awareness of local lagoon land and water management issues. With the data results having revealed no problems with the water quality in the Litchfield Shire, the emphasis is on a preventative approach.

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Community wetland management: The Northern Land Council's Top End Indigenous People's Wetlands Program

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Abstract

Aboriginal people own 85 per cent of the Northern Territory coastline and many of the vast and important sub-coastal wetlands. The Northern Land Council-facilitated *Top End Indigenous People's Wetlands Program* (TEIPWP) was conceived to assist Aboriginal land owners prepare management plans for some of these wetlands. Land owners have control over the pace and process of the program in their areas. The TEIPWP is developing into a good example of cooperation between individuals and agencies.

This paper describes the TEIPWP and, in particular, work undertaken in two major wetland sites, the Blyth-Liverpool system near Maningrida and the Arafura Swamp in central Arnhem Land.

Keywords: Aboriginal land owners, wetland management, sustainable resource utilisation

1 Introduction

The Northern Land Council (NLC) is a statutory body set up under the *Aboriginal Land Rights (Northern Territory) Act* (1976). The NLC has a legal obligation to consult with land owners and to help them manage their land. To achieve this the NLC has set up a small group called the Caring for Country Unit. Caring for Country is concerned with helping Aboriginal people manage their country – and this is everything … sandstone, savannas, wetlands and seas ... and to foster developmental enterprises (Taylor 1995). To achieve this, both Aboriginal (or traditional ecological) knowledge and non-Aboriginal (or contemporary/scientific) knowledge is used.

Aboriginal people have capably managed their land for thousands of years and there would be no great need for external advice or assistance if it were not for new pressures and faster rates of changes. These are pressures from unfamiliar sources, such as weeds and feral animals, infrastructure development and also Aboriginal people's desire to pursue economic independence. Traditional Aboriginal management practices often do not effectively address these issues – bridging the divide between traditional practices and contemporary problems is where the Caring for Country Unit can be of assistance.

Aboriginal people own 85% of the 'Top End' coastline and therefore most of the vast and important sub-coastal wetlands in the Northern Territory (NT). Top End wetlands are in a relatively pristine condition (Storrs & Finlayson 1997). They are recognised as having high national and international conservation value (Whitehead et al 1990) and are also recognised for their cultural significance because of a long and unbroken tradition of indigenous management. However, wetlands in the NT are under threat from various sources such as introduced species, both animal and plant (Storrs et al 1996), changed fire regimes and possible overuse of resources due to commercial harvesting activities (Storrs & Finlayson 1997). Such threats have significance for Aboriginal people because they can cause damage to food resources or sacred places.

2 The Top End Indigenous People's Wetlands Program

The NLC-facilitated *Top End Indigenous People's Wetlands Program* (TEIPWP) was conceived to assist Aboriginal people prepare management plans for their wetlands. The TEIPWP employs a Wetlands Officer who operates within the NLC Caring for Country Unit. The strategy adopted is 'total catchment management' coordinated amongst the NLC regions. At the local level Aboriginal landowners have control of, and participate in, the planning process and implementation of wetlands management. Ten important wetlands have been initially identified for the program:

1. The Arafura Swamp
2. Blyth-Liverpool Floodplains and Boucaut Bay System
3. Daly-Reynolds Floodplains-Estuary System
4. Moyle Floodplain and Hyland Bay System
5. Murganella-Cooper Floodplain System
6. Arnhem Bay System
7. Blue Mud Bay System
8. East Alligator River Middle Reaches
9. Fitzmaurice River Middle Reaches
10. Little Moyle Floodplain

More recently it has been suggested that Gulf of Carpentaria, Joseph Bonaparte Gulf and the wetlands of the Barkly Tablelands be added.

2.1 Program aims

The major aims of the program are to undertake a technical review of the major wetlands, determine what information is documented and identify gaps. Then, through consultation with traditional owners, identify what things are important (eg mimosa control) and what land owners need for 'wise' management. This information will be used to help Aboriginal communities develop and implement wetland management plans. It is envisaged that wetland management planning for 'one or two sites' will be undertaken during the initial phases of the TEIPWP.

2.2 Funding the program

The three year program, which was instituted in early 1996, is funded by Environment Australia from its National Wetlands Program. The funding is limited, covering the Wetlands Officer's wage. It does not contain money for consultation, management planning or implementation. Therefore a large part of the Wetlands Officer's job is to obtain resources and research assistance where available. Despite this limitation the program seems to be developing into a good example of how cooperation between individuals and agencies can be used to benefit Aboriginal communities who are interested in land management.

2.3 Technical advisory committee

A Technical Advisory Committee (TAC) was set up under an informal agreement between a number of organisations not only to provide technical advice, but also to increase access to government resources and services, expedite efficient and effective allocation of technical assistance, avoid duplication of research and increase funding opportunities. The TAC includes: Professor Marcia Langton, Director, NTU Centre for Indigenous Natural and Cultural Resource Management (CINCRM); Professor Greg Hill, Director, NTU Centre for Tropical Wetland Management (CTWM); Dr Max Finlayson, Manager, Wetland Protection and Management section, ***eriss***; Peter Whitehead, Principal Wildlife Research Officer, Wildlife Research, Parks & Wildlife Commission NT (PWCNT), Rod Applegate, Director, Land Resources Branch, NT Department of Lands, Planning & Environment (DLPE); Dean Yibarbuk, Chairman, Bawinanga Aboriginal Corporation (BAC); Piers Barrow, Senior Project Officer, Natural Resource Management, Kakadu National Park; and Tom Scotney, Project Officer, National Wetlands Program, Environment Australia.

3 The importance of wetlands

Wetlands are important in that they provide a home for plants and animals (ie they support abundance and diversity), they filter pollution, they provide clean water for domestic, industrial and agricultural use and they can be used for recreation. But most importantly, in the context of this paper, wetlands support indigenous cultures in many places around the world, providing food and other resources and a traditional way of life for the people.

Research in the Kakadu area has shown that wetlands are the focus of resource utilisation by Aboriginal people (Russell-Smith et al 1997). Until quite recently Aboriginal people experienced their leanest times when wetlands were inaccessible during the Wet season. Latterly wetlands are also providing opportunities for sustainable economic development. Economic independence, self-determination and self-government are major aspirations of Aboriginal people today.

In a worldwide perspective wetlands, especially coastal wetlands, are being destroyed through development. With the loss of wetlands traditional ways of life are being lost. An international effort is required to save the remaining wetlands, and Australia is playing an important role in this. Australia has signed a number of international conventions, some states and territories have wetland policies, and through Environment Australia there is support for various programs such as the TEIPWP that promote the wise use of wetlands.

4 Wetland management planning

One of the primary tasks of the TEIPWP is to undertake an issues and needs analysis for the major wetlands on Aboriginal lands. This has broadly been addressed in a document entitled *Overview of the conservation status of wetlands of the Northern Territory* (Storrs & Finlayson 1997). Further to this the PWCNT have received a $25 000 grant from Environment Australia to develop a wetland Geographic Information System (GIS) database by collating all their inventory information on wetlands. Part of the contract agreement provides NLC with access to the databases. Remotely sensed imagery of a number of sites has been obtained by the NLC and provided to the NTU, Latrobe University and the Australian Geological Survey Organisation, all of whom are currently enhancing the data.

The TEIPWP is invited into an area by land owners who remain in control of the process. Community conservation ranger programs have been initiated at a number of sites collaboratively by communities and the Caring for Country Unit. Caring for Country Unit staff talk to the rangers about what needs to be done, who can do it, where and when to do it, and who can help. The process is then issues driven. Projects are developed for each issue and rangers assigned to projects. The challenge is to foster the use of indigenous knowledge while delivering non-indigenous management training to the rangers so they have access to both knowledge bases. The expectation is that when research is done it is a two way learning process involving Aboriginal people.

Indigenous projects include the use of fire as a hunting tool or for managing the vegetation, protection of sacred sites, mapping of cultural boundaries, hunting and collecting of food etc. Non-indigenous projects include such things as mapping of wetlands, establishing GIS databases, animal and plant surveys, control of introduced species, and research into the commercial harvest of wildlife (a topic in which Aboriginal people are very interested). All these projects can be brought together under a management plan.

The drafting of a management plan is about establishing what people want to use the wetlands for, what work needs to be done (projects) and how people go about getting the work done. It is about planning for the future as, without effective planning, it is hard to achieve goals. As with other communities, Aboriginal people within a community have different aspirations for their wetlands which can cause conflict. The planning process can help to clarify different priorities and in some situations offer satisfactory compromises.

4.1 Blyth/Liverpool River systems

For its first year of operation, the TEIPWP focussed on the wetlands of the Liverpool/Blyth River systems in Central Arnhem Land – an area in which the Bawinanga Aboriginal Corporation (BAC) operates near Maningrida. This area was chosen because of the excellent administrative infrastructure of the BAC and the fact that some land management planning had already occurred. The latter was associated with the formation of a community ranger program (the Djelk Community Rangers) under a previous Caring for Country training program. Through the TEIPWP government help has been organised, requests for government funding for specific projects have been made, and the community is being helped to draft a management plan for the wetlands.

Djelk Rangers are now receiving more advanced training through participation in the NTU's Certificate IV in Resource Management and a broader world view is being offered through participation in conferences and workshops. In 1997 they also undertook coxswains and small boat handling training. In September 1997 the PWCNT conducted a 10 day ranger training camp. This involved senior research staff and park rangers working alongside the Djelk Rangers and other Aboriginal community rangers to undertake vegetation and fauna surveys.

The Djelk Rangers are involved in projects to follow up treatment of *Mimosa pigra* (mimosa) infestations near Maningrida in collaboration with the DPIF Weeds Branch (the early intervention of this incursion was brought about through education, training and resourcing). The management of feral animals, particularly pigs, which are causing damage to sites of both natural and cultural significance is being furthered in collaboration with the PWCNT who are seeking research funds.

eriss has been undertaking a wetland inventory, including plant, macroinvertebrate and fish surveys. These surveys are undertaken collaboratively with Djelk Rangers and some rangers have visited ***eriss*** in Jabiru to take part in field and laboratory studies. The BAC are setting up a GIS for biological and cultural purposes with assistance from the NTU, while erosion control works are being undertaken by the DLPE.

A crocodile egg harvesting and incubation program facilitated by Wildlife Management International Pty Ltd (WMI) was successful over the 1996/97 Wet season and was very well supported by the Djelk Rangers. It is envisaged that the program will be completely controlled by the Djelk Rangers in the 1997/98 Wet season.

The BAC in collaboration with Wildlife International Pty Ltd had planned a trial harvest of 100 saltwater crocodiles in 1997 for the skin trade and for subsistence consumption of meat, the first such harvest in 20 years. After an initial harvest of six adult crocodiles in September the program has been put on hold following objections to the harvest by members of a clan for whom the saltwater crocodile is a principal totem. It is difficult to forecast an early resolution of the issue of adult harvest, however the totemically affiliated group have not taken a negative stand on egg harvesting or incubation.

Plans by the BAC to take a lead role in the revitalisation of the trepang industry are less well advanced. Since the large-scale trepang industry involving Aborigines and Macassan ended early this century there has been only desultory activity despite the fact that Australia probably holds a large portion of the global trepang resource. With funding from a variety of sources, the BAC have attracted interest in studies to determine core areas of abundance, variability and preferred habitat characteristics. In areas of known occurrence, the research will model biomass dynamics and measure the effects of harvest on selected sites (Carter & Yibarbuk 1996).

Research arrangements within all projects emphasise local benefit from collaboration and involve the community rangers and equipment as essential parts of the research teams. Research planning is carried out collaboratively and the community receives ongoing reports of research results.

The BAC has built a ranger station about 20km out of Maningrida which incorporates a field laboratory. This will allow more technical aspects of collaborative research to be carried out on Aboriginal land and give rangers the opportunity to observe and participate in scientific studies and surveys. The vision of the Djelk Community Ranger program includes construction of a more extensive training and research centre to focus on further development of collaborative research aimed both at maintaining the near-pristine natural biota and in developing sustainable uses of wildlife. This has a dual aim of conserving biodiversity through sustainable use and creating a future economic base for the Aboriginal community.

Staff from ***eriss*** have been collating available information from the Blyth-Liverpool systems into a document (Thurtell et al 1998) that will form the technical basis of the management plan (which will then be developed through participatory planning with the community). Several drafts of this document have been passed around to principal players and it is now ready for wider distribution and input from others.

4.2 Arafura Swamp

Now that management planning in the Blyth-Liverpool systems is underway, the TEIPWP's focus of attention has shifted to the Arafura Swamp. The Arafura was chosen because of its proximity to the Blyth-Liverpool wetlands (ie it is the next catchment to the east) and, being on the Interim Register of the National Estate, it was hoped that management funds for conservation initiatives could be attracted. The Arafura is Australia's largest tropical freshwater swamp.

The TEIPWP is setting up a land management board made up of representative land owners for the Swamp and its surrounds. There are land management issues in the Swamp which need to be addressed urgently, for instance there have been 11 incursions of the rampant weed mimosa since the early 1990s. As well, there appears to be a lot of interest from funding agencies and researchers who want to involve themselves in the area. The trick is to facilitate this outside interest and resources while addressing the land management issues but, most importantly, ensuring that the land owners are kept in charge of the process. It can be a delicate balancing act!

A number of meetings have been held in Ramingining with members of the Interim Arafura Swamp Land Management Board and other land owners about future directions in land management in the Swamp. There appears now to be fairly general support for the establishment of community ranger programs in the northern part of the swamp. The CFC Unit on behalf of Ramingining Resource Centre and the Council have submitted a funding application to the NHT to train four community rangers.

Existing and planned community ranger programs in the south-east part of the Swamp have very high community acceptance, but are currently suffering from extreme resourcing problems. On behalf of several communities, Dr Neville White from Latrobe University in collaboration with the NTU Centre for Indigenous Natural and Cultural Resources Management (CINCRM) is seeking support funding for community rangers for weed control and other land management in the south-eastern part of the Swamp.

In October 1997 a collaborative research team offered their services to undertake some baseline geomorphology work in the Arafura Swamp. The research team was made up of the Australian Geological Survey Organisation's (AGSO) Coastal Lands Project Group led by Dr Trevor Graham and a group from the ANU Division of Archaeology and Natural History led by Professor John Chappell (and including Professor Rhys Jones). Apart from providing baseline data for management planning, the paleo-geomorphologic work in the Swamp will give land owners information on how that area has responded to environmental pertubations over the last 100 000 years or so and how, amongst other things, it might therefore respond to anticipated sea level rise due to global warming. Land owners were fully consulted over the work program and accompanied researchers into the field. Researchers will return to the community to explain their findings.

Members of the DLPE's Water Resources Division (Ursula Zaar and Geoff Prowse) have been undertaking a Landcare-funded program to determine the underground hydrology of eastern Arnhem Land. Field work in the Arafura Swamp area is currently being undertaken. Dave Williams, a surface water hydrologist with Water Resources, has been instructed by his Division Head to undertake a hydrological modelling exercise of the Arafura Swamp. This work will be dependant on obtaining further funding and will be undertaken in collaboration with Professor Chappell and the local landowners.

A major achievement for the TEIPWP was holding a research workshop on the Arafura Swamp in Darwin on 24–25 November 1997. The TEIPWP received $30 000 from the Land & Water Resources Research & Development Corporation to consult with land owners and conduct the workshop, which was facilitated by CINCRM. The main purpose of the workshop was to conduct an audit of previous relevant research and to flag future research interests from non-local agencies. This information will be important in planning how to use research in the development of on-ground capacity for land management, such as providing support to the evolving community ranger groups in the region. This was the first occasion for the sharing of research results among more than 50 individuals from a range of institutions. The workshop will undoubtedly result in better collaborative research in the future.

5 Future directions

Although the TEIPWP is achieving some degree of success, the broad plan of adequately addressing management planning on the most important wetland sites on Aboriginal land in the Top End of the NT is contingent on receiving adequate funding. The TEIPWP was successful in obtaining a commitment for funding from the CRC for Tropical Savannas for a half-time position to undertake a research and training needs analysis in the Arafura Swamp. More recently Environment Australia's National Wetlands Program have granted money for half a position for a wetland management coordinator for Central Arnhem Land. These monies could be used for one full time position or a number of part-time positions. Negotiations are proceeding.

Once a person(s) is engaged to carry on with wetland management in Arnhem Land it is envisaged the existing NLC Wetlands Officer position will shift the focus of activities to wetlands on the western side of the NT (eg Wagait, Daly/Port Keats etc) to 'kick start' awareness and initiate wetland management planning in that area.

Further to this there is a need to adequately resource the partner organisations of the TEIPWP (figure 1). For instance the AGSO/ANU team will need some funding over and above their own to complete the Arafura Swamp geomorphology (and extend the work to other areas), DLPE Water Resources will need some funding to undertake hydrologic modelling, PWCNT will need funds to undertake biological surveys, while ***eriss*** will require funds to undertake the collation of information for the TEIPWP. Depending on the availability of funding, and continued consultation and collaboration with traditional owners, the TEIPWP could develop into a truly world class program.

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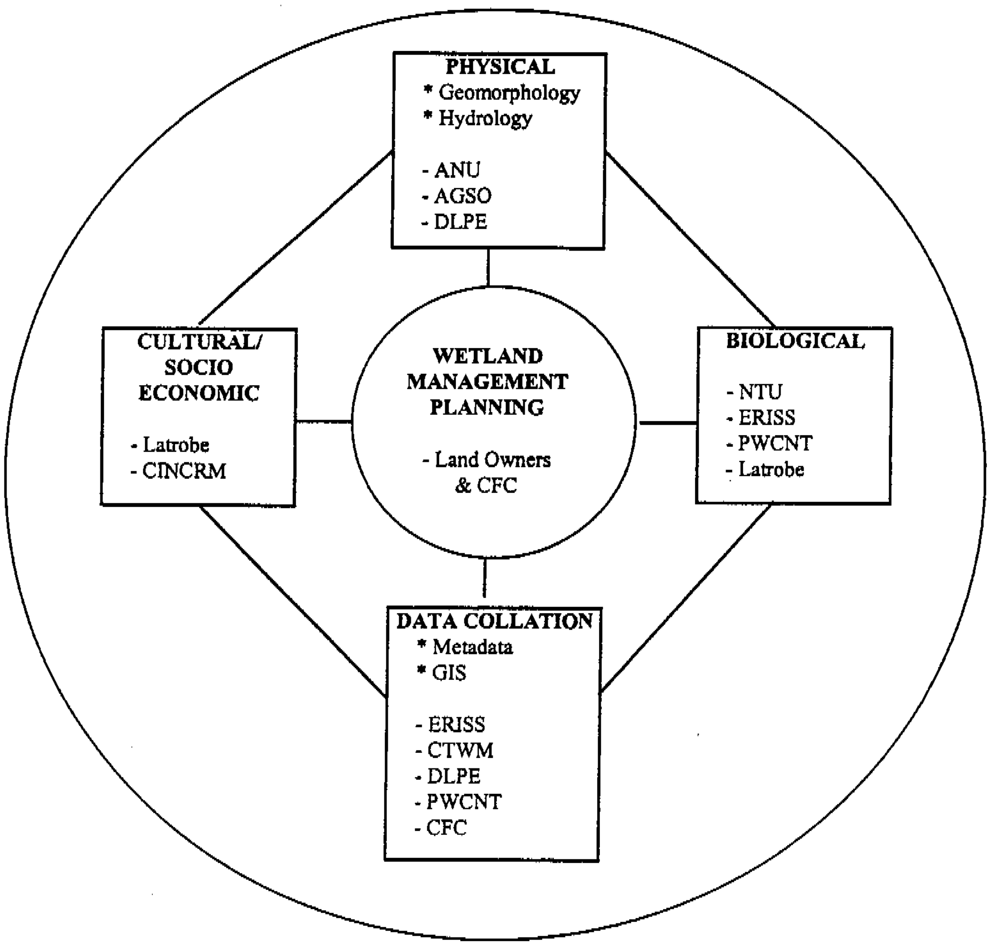
Figure 1. The Top End Indigenous People's Wetlands Program



ORGANISATION ACRONYMS

AGSO – Australian Geological Survey Organisation – Geohazards, Land and Water Resources Program

ANU – Australian National University – Division of Archaeology and Natural History

CINCRM – Northern Territory University – Centre for Indigenous Natural and Cultural Resource Management

CTWM – Northern Territory University – Centre for Tropical Wetland Management

CFC – Northern Land Council (NLC) – Caring for Country Unit

DLPE – NT Department of Lands Planning and Environment – Water Resources Division

ERISS – Environmental Research Institute of the Supervising Scientist – Wetlands Protection and Management Branch

La Trobe – La Trobe University – School of Genetics and Human Variation

PWCNT – Parks and Wildlife Commission of the NT– Wildlife Research Division

Aboriginal management of wetlands and the Dead Sea Scrolls

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(Adapted from transcript)

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1 Introduction

I teach the Lands, Parks and Wildlife Management course at the Jabiru Regional Centre for the Northern Territory University, and I come from a national parks background. I spent 15 years working as a ranger for the South Australian National Parks and Wildlife Service before coming here, and when I arrived, people said to me "Can you help our Aboriginal ranger trainees here in Kakadu with their literacy?" So I started as a part-time tutor in 1986 and soon became a full-time lecturer for various subjects.

This morning I was asked to replace a lecturer who was unable to turn up, so with less than a few hours notice I decided to talk about the importance of the Dead Sea Scrolls in wetland management in the Top End. I feel this is relevant because it brings together the temporal cultural and scientific elements of wetland management in the Top End.

2 Time, tradition and the Law

The Dead Sea Scrolls are about 2100 years old. The wetlands here in Kakadu are about that old too. They're not very old at all. That's an interesting point, because I've just come from the Bushfires '97 Conference in Darwin, where experts on fire gathered from all over Australia to present their opinions on fire management. At the conference, several speakers got up and said things like 'Aboriginal people have been managing this country adequately for the last 40 000 years and there's got to be a lot of knowledge there that we can use'. Well that's partly true and it's partly false. Nobody here is 40 000 years old for a start. Whether balanda (non-Aboriginal) or Aboriginal, we have all learned what we've learnt from our fathers and mothers, depending upon who we listen to the most. In traditional Aboriginal society people learn most from their uncle, who is himself usually not more than 30 or 40 years old. The wetlands themselves are not very old either. They're not 40 000 years old, they are only 2000 years old, if that.

If we read the Dead Sea Scrolls, we can read the thoughts, intentions, aspirations, problems and the Law of a people who lived on the earth 2000 years ago. We can read it in detail, draw observations from the scrolls and know the people quite intimately. We can't do that with Aboriginal people, because Aboriginal people had an oral tradition, not a written tradition. That is something we must remember, because it changes every generation and so the tradition we have here to draw on, in that sense, is only one or perhaps two generations old.

Tradition is formed in a very short time. Anyone who has been in land or parks management will know that! For example, when you go to a remote campsite and there's a man there and you ask him for his camping permit, he says 'But I've been coming here for years'. If you happen to have been the ranger there for the past 10 years, you know he only arrived last year for the first time. Traditions are often of that nature.

If you read the Dead Sea Scrolls today, those people may as well have come from Mars, because of the irrelevance of much of what they write to the modern technical society and the scientific culture. They would not know how to cope if you put them into a spot here and now. They come from an academic tradition, but it is an academic tradition of the Law. Aboriginal people similarly come from an academic tradition with regard to the Law – it is an oral tradition, but academic nevertheless. And the Law does funny things. People do funny things with the Law. Some of those things are long-standing in human society. One might say that the Law expressed in the Dead Sea Scrolls is in essence the same as the Law that's expressed in Aboriginal society; it is non-materialistic to the same degree, it puts the sacred above the material and people somewhere in between. (Modern Australian society puts the material above people and the sacred somewhere at the bottom, attaching no sanctions to it whatsoever, so we have the opposite effect.) There are some, perhaps many aspects in the laws of Middle Eastern society which are identical to Australasian society's traditional law.

2.1 What is relevant today?

Something from the Dead Sea Scrolls which I thought might be relevant today is the old law, going right back to the Law of Moses and probably about 4000 years old, that 'you shouldn't lead a blind man into a ditch'. That was the Law. So you mustn't believe a word I say today, and don't believe too much of what you've heard in the whole time you've been here! It is better that you don't. It is better that you check up on everything. That is what I tell all my students, especially Aboriginal students, because I want them to check up. I don't want them to sit back and believe everything I tell them, because I might be wrong. Science, as you well know by this stage, is a house of cards. It is people's deductions built on other people's assumptions. If something that somebody assumed at the bottom of the stack is later proved incorrect, then what are you left with? You have to remove the card from the bottom of the stack. Some people believe that the house of cards will still stand up even though the whole bottom row is missing! So I say be careful, especially when thinking about the relevance of traditional Aboriginal land management in the modern world.

3 Myths and misconceptions

I agree with the statement that Aboriginal people were quite adequately managing this country for thousands of years – perhaps not the wetlands for all that long but certainly the dry country – but recent influences have upset the whole process and that is where our role comes in as scientific land managers, especially in terms of wetlands.

Here we have to remember something else. We have come to assume, over the last two decades (and it's a balanda myth, not an Aboriginal myth, although Aboriginal people have come to believe it and to promulgate it) that Aborigines, as hunter-gatherers in Australia, actually knew what they were doing. Now when you read the Dead Sea Scrolls, you read about people with a very high level of intellectualism. Those people were managing the Middle East 2000 years ago in a time when the Middle East was more fertile, had a higher rainfall than it has now etc – and yet we can see what has happened to the Middle East as a result of several hundred years of management. Our western scientific land management culture has developed out of that civilisation, and we know for a fact that we haven't known what we've been doing for thousands of years!

3.1 Could we destroy the earth?

There's a very interesting set of books in the Dead Sea Scrolls called the Apocalyptic Books. The Jews at that time had quite a number of Apocalyptic books available to them. One of these books, written at about the time when the very last Dead Sea Scrolls were being stowed away in caves, is the Book of Revelation which we now have in the New Testament. There is an interesting verse in there which says 'God will destroy those who destroy the earth'. For hundreds of years this verse was translated as 'God will destroy those who *corrupt* the earth', because at the time it was written and in subsequent centuries up until this century, it was impossible to conceive that man could destroy the earth.

In the mid-1800s people began to think that perhaps we could manage the earth better than we are, and there is quite a lot of writing about that, even in Australia amongst the colonists. There is one famous quote from about the 1860s that 'surely God meant Australia to be used for a purpose higher than to be tottered over by the squatter's scabby sheep?' which I think is a marvellous quote. I think what he meant was that the sheep should have been moved off and they should grow wheat, but the point was that they were thinking about management back then.

By the 1950s people were sounding a note of caution; 'hey, it's still out there to be exploited, but perhaps we'd better be careful how we do it because we've just about discovered everything by now'. By the 1960s, Rachel Carson was saying 'hang on a minute, it's all come unstuck and if we don't do something about it soon we'll have an environmental disaster'. By the 1970s people were saying 'it's not only possible that man might be able to destroy the earth, but we think it's inevitable'. And of course now in 1997 we are in a critical period.

3.2 Aboriginal people and conservation

Where does my role with Aboriginal people come into this? The idea of a big national park in this area was first mooted in the 1960s by conservationists. Then they discovered uranium and that put the cat among the pigeons. Eventually Kakadu was established as a bit of a tradeoff; the Aboriginal people could have their land if they allowed mining to go ahead, and the conservationists could have their national park if they supported the Aborigines' claim to land, and so followed a domino effect by which the federal government managed to get its uranium mine with the least possible political damage.

Of course we all know what kinds of social damage has occurred since, and the environmental damage which perhaps could occur, but I won't go into that. The point is that Aboriginal people were invited to play a role in the management of Kakadu very early in the piece, on the basis that they would be managing the Park within the first 10 years. Now that was a promise made to them, a genuine belief of the bureaucrats in Canberra and of conservationists generally.

You see, conservationists thought that Aboriginal people were also conservationists. That was the first myth. Hunter-gatherers are not conservationists. Hunter-gatherers are exploitative, just like agriculturalists or pastoralists etc. They are producing food and they are interested in the largest amount of food for the least amount of effort. That is their first priority. Hence what Aboriginal people see as an excellent or perfect landscape might not be what conservationists think is an excellent or perfect landscape, from a biodiversity or other point of view. They are managing towards quite a different goal.

3.3 Aboriginal ranger training program

3.3.1 Misunderstandings

So very shortly after the first Aboriginal ranger training program started, problems began to arise in terms of joint management. There were obvious discrepancies between the aims of the Aboriginal people – even the Aboriginal rangers – and the balanda rangers, the balanda administration and conservationists who were supporting areas like Kakadu. However, generally only the balanda rangers actually knew about that. The Aboriginal rangers didn't know there was a conflict either, because they didn't know enough about what balanda rangers did. They didn't think the balanda rangers did anything! The Aboriginal rangers had done a crash course (6 months) on the public service, among other things, and then were put into ranger positions. They didn't know how the public service worked after just 6 months, they didn't know anything about what we would call conservation land management, and they didn't even know what they were expected to do each day in their work, in terms of what they were being paid for.

For example, one man said to me 'I've got a couple of extra children now, do my wages go up?' I asked 'Why do you think your wages should go up?' He replied, 'Well, everybody else's do'. If you are living on welfare payments and you have more children, your benefits go up, so he thought his wages did that too. He didn't understand that his wages were based on the fact that he was supposed to turn up to work every day. There were a lot of such things that Aboriginal people did not understand.

3.3.2 Communication problems

Communication difficulties also arose. One senior ranger was invited to District Supervisors' meetings because he was considered very astute and articulate, and the supervisors said to me 'We don't understand where this guy is coming from, because we know he has opinions on particular issues, and we'd like him to express them in our meetings, but when we invite him to the meetings he sits there and says nothing while we discuss the subject!' They were becoming quite frustrated with the fact that they couldn't seem to get any dialogue between the Aboriginal people and the supervisors, even on issues upon which they knew Aboriginal people had well-founded opinions.

So I went along to a literacy course I was teaching, and, as I do with all my students, I asked this senior ranger 'Why are you doing this course? What can we give you?' He said 'I'd really like to be able to read and understand what the District Supervisors read and understand'. I asked 'In what way do you feel you're falling short?' 'Well,' he said, 'I go along to the District Supervisors' meetings and I don't understand a word they say!' So he wasn't saying anything because he didn't know they were discussing the topic he was interested in. Nobody had realised that.

3.3.3 Solutions

The Kakadu National Park Board of Management, which was established as an advisory board, recognised this problem, as some of the members were Aboriginal rangers who knew the shortcomings of the system. The Board decided to have a better ranger training program. They got it started and abolished what was by then an 18 month limit, leaving it open-ended with the requirement that the trainees must get to certificate level.

We held an Open Day at NTU Jabiru (then the NT Open College) so they could look at relevant courses that were available, including courses at Batchelor College, which is an Aboriginal College. The Board of Management decided on the NT Open College course, now the NTU course. I was surprised as I thought they'd prefer their people to be trained as rangers at the Aboriginal College. Their reason for this decision was that they wanted their Aboriginal rangers sitting in the classroom with balanda rangers, so the Aboriginal people would understand that their certificate was not just an Aboriginal qualification, but a broadly-based, mainstream qualification for everybody. I thought that was a good decision, and the training has been underway since.

It is rather interesting because we now have Aboriginal rangers who, of their own volition, ask for their own classes (without balanda students) to enable them to work at their own pace. They feel that if other Aboriginal people in the community who'd like to be rangers see them in the course and succeeding, they may think they can do it too. At NTU Jabiru we try to be flexible wherever possible and encourage more Aboriginal people to come and study.

3.3.4 Training today

So training has progressed from a '6 month crash course then throw them to the wolves' (from which the attrition rate has been huge over the years) to today's scenario, in which there are a number of Aboriginal rangers undertaking study in a range of subjects.

4 Common sense versus Science

The reason why Aboriginal people are undertaking study (and they're particularly interested in scientific subjects) is because they don't have that knowledge. They only know certain things. When you're a hunter-gatherer you live on common sense. Common sense is different to science. Common sense tells you that the sea is higher than the land because the waves fall onto the land. Common sense tells you that the sun comes up on one side of the earth and goes down on the other side, and that there's probably another sun the next day because otherwise where did that one go? Common sense tells you that the earth is flat. But common sense is absolutely indispensable for survival. However, in order to understand things at the level we now need to know for survival, we have to look at things in a scientific way, and many Aboriginal rangers are learning this as well.

Aboriginal people need to know more than they did before. They know lots about barramundi and other fish that they catch to eat, but they know very little about the small fish the barramundi eat. They don't know the complexities of the food chain; they didn't need to know while there were plenty of barramundi there. Now, when animals are likely to be threatened by influences elsewhere, Aboriginal people need to know scientific management. In a recent successful, ongoing initiative in Kakadu, Aboriginal rangers tag turtles to find out what the turtles are doing. In fact this turtle survey program was first proposed in about 1987 by an Aboriginal ranger. He was opposed at the time by scientific staff who felt that rangers shouldn't be involved in scientific work, especially Aboriginal rangers; they thought it was better to bring in consultants from elsewhere. Yet Aboriginal rangers have since proved to be keen participants in research projects.

So, to put it in a nutshell, we are in a new era. We are all having to learn rapidly, and Aboriginal people are being swept along by the same wave. We are finding out things for the first time and so are they. The idea that Aboriginal people have to come up to speed because these jobs must be done, is a very valid point. There are Aboriginal people who acknowledge this. It is very important that we do not ride roughshod over their rights as land owners, but the clue to proper management of wetlands in the future, here in the Top End in particular, is education – for everyone. The more Aboriginal people get involved with education, and the more they are helped along with information, the better.

eriss has had a very bad reputation in this area for non-communication. It is very easy for academics to keep their heads down at their work because they are often very specialised people and can forget about the rest of the outside world! Many Aboriginal people don't know what ***eriss*** does. They think that scientists know nothing. They quite genuinely believe that balanda rangers with university qualifications, recruited from other states, know nothing. This is because balandas have been busy telling Aboriginal people that they know everything, which is also wrong. The more we tell them that, the greater the disservice we do them. There is a lot of work yet to be done to redress this problem.

5 Conclusion

Well, I am going to finish with this poem about indicator species. A canary in a cage was once a good indicator species – miners would take a canary into the mine and if the canary fell off its perch they got out of the mine rapidly! But the indicator species studied here in Kakadu are macroinvertebrates, considered to be good species for monitoring environmental change. Macroinvertebrates are at the very bottom of the food chain. As we are at the top, there may be a bit of a paradox in watching them for indications that we might be in trouble!

Indicator Species

Sunk in substrate Macroinvertebrates
Wiggle their tails and claws
Beckoning enticing friends and relatives to
Macroinvertebrate jaws
Macroinvertebrates love their mud
Safe beneath both fire and flood
Steadfast resolute they shrink not from their
Macroinvertebrate cause

Casebound cryptic Macroinvertebrates
Scrabble their river beds
Gathering and shaping tiles to decorate their
Macroinvertebrate sheds
Macroinvertebrate grope and graze
Safe from predatory gaze
Blissful oblivious they fear not for their
Macroinvertebrate heads

Thrice transvestite Macroinvertebrates
Struggle to find a mate
Fluttering and searching moonlit billabongs for
Macroinvertebrate bait
Macroinvertebrates nymphs may be
Even so some may fly free
Lusty purposeful they set seal to their
Macroinvertebrate fate

All unwary Macroinvertebrates
Dazzle in Man's bright light
Pickling and probing Man must study their
Macroinvertebrate plight
Macroinvertebrates know their place
Not quite so the Human Race
Poisoning polluting Man can't last but
Macroinvertebrates might

(AG Spiers © 1992)

Question: In terms of providing Aboriginal people with the science, is there any risk that we might be diluting their culture even further, losing their cultural values or characteristics? What is your interpretation of that?

That is a very good question. Aboriginal people are always trying to say 'Look, don't you understand that culture changes? Don't you understand that Aboriginal culture is not the same from one side of Australia to the other? We're different.' And we never listen to them. We like to believe that they have the oldest continuous culture in the world, and that Aboriginal culture is the same all over Australia. I suppose some Aboriginal people have picked up on this popular belief and now say 'Ours is the longest continuous culture in the world'. Well, that's just another balanda myth.

The oldest continuous culture in the world is human culture. Aboriginal people brought a fully-fledged culture with them when they came across to Australia, and what they brought with them came from thousands and thousands of years in their place of origin. It comes from the same source the Dead Sea Scrolls came from. Human culture is the same all over the world in terms of its source (unless you believe in convergent evolution of *Homo sapiens* in different parts of the world at different times – I don't). Like all other human beings, Aboriginal people are very keen to adapt their culture if they find something that is worthwhile. They only discard those bits of their culture that they don't want or don't consider worthwhile. Now in terms of answering that question, I'd be making a value judgement. I'd be saying 'Yes, well, it's a pity they've lost that bit because it was really important'. Well it wasn't important to them if they lost it.

(*Tape ends*)

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Coastal management in the Alligator Rivers region

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Abstract

The Alligator Rivers Region is of great cultural and conservation value. The coastal zone wetlands, in particular those contained within Kakadu National Park, have been the centre of much research. This research base has been used to assess the vulnerability of the coastal wetlands to climate change and sea level rise. Estimates of change were based on a climate change scenario developed by IPCC and CSIRO. Environmental responses were estimated from the wealth of biophysical data available. However, no actual measurements were made to confirm the predictions. In order to develop a better model and management strategies an integrated monitoring node has been established. The initial components of this node include further coordination and collation of existing data and information, and the development of a framework for monitoring of large scale change processes on the floodplain wetlands.

Keywords: coastal management, vulnerability, climate change, sea level rise, monitoring

1 Introduction

In 1994 the Commonwealth Government of Australia, through the Department of Environment Sport and Territories, commissioned eight Australian studies to establish regional differences in methodology required to assess the vulnerability of coastal land to potential change in climate and rise in sea-level. The objectives of the projects were to establish data requirements for vulnerability assessment, determine the adequacy of existing information, ascertain the capacity of existing management structures to cope with potential issues devolving from predicted climate change and rise in sea level, and to establish the preparedness of management agencies to confront the issues.

Two case studies were conducted in the Northern Territory, at Darwin and Kakadu. The case study of the Alligator Rivers Region, and Kakadu National Park in particular, included the extensive tracts of wetland on floodplains bordering the principal rivers of the Region (Bayliss et al 1998). The Alligator Rivers Region (ARR) is a highly dynamic environment. It is subject to extreme rates of change due to seasonal and interannual variation in climate, storm incidence, sea-level fluctuation, and river discharge. Since management has had to take account of this variability its principles and policies may differ from those applied to management of the less variable, temperate environments of the southern coasts. Management of coastal and wetland areas on the western flank of the ARR, is vested in the departments of the Northern Territory Government, whereas Kakadu National Park is the responsibility of the Commonwealth Government. Day-to-day management of the Park is the responsibility of Parks Australia-North (PAN) acting on behalf of, and in consultation with the Kakadu National Park Board of Management.

As a consequence of the vulnerability study a coastal monitoring node was established at the Environmental Research Institute of the Supervising Scientist in Jabiru, Northern Territory. The process being adopted to develop this node is described along with an assessment of the scenario of climate change and management responses (see Bayliss et al 1998, Finlayson et al 1997).

2 Regional setting

The ARR encompasses the catchments of rivers draining into van Diemen Gulf between Point Stuart and the eastern bank of the mouth of the East Alligator River, including Love Creek (Bijibiju) and the Wildman, West Alligator (Marangayu), South Alligator and East Alligator Rivers (fig 1). The region is part of a broader, biophysical region encompassing all of the coastal wetlands from Cape Hotham to the Ilamaryi River on the western flank of Coburg Peninsula. The region lies to the east of Darwin (fig 1) and includes all of Kakadu National Park.

The major part of Kakadu National Park is drained by the South Alligator and East Alligator Rivers, with the smaller West Alligator and Wildman Rivers draining the north-western portion of the region. The Mary and Katherine Rivers drain a minor portion of the south-westerly part of the region and they are not considered further. The rivers are fed by a network of ephemeral creeks and drain into van Diemen Gulf, in the north. The combined catchment area of the four major rivers is approximately 28 000 km^2, about 8000 km^2 greater than the size of Kakadu National Park

Coastal lands of the region are low in elevation, which makes them susceptible to sea level fluctuation. Floodplains generally lie between 3 and 4 m above Australian Height Datum (Williams 1969, Woodroffe et al 1986), below the more elevated Koolpinyah Surface, which is characterised by a laterized profile and above 5 metres in elevation (Wasson 1992). This makes them only 0.2 to 1.2 m above mean high water level. Arguably, a change in climate would substantively affect the physical and biological conditions of the coastal wetlands that constitute the greater part of the coastal plains, especially if significant rise in sea level occurs. In turn, changes to the physical and biological conditions are likely to have cultural, social and economic ramifications. Ultimately, any changes in the environmental conditions will affect the way in which the natural resources of the Region are managed. The challenge is to ensure that management recognises and can cope with such change.

3 Management structure

Kakadu National Park is the most important natural, cultural, recreational and tourist resource in the region. The importance of its natural and cultural heritage values are recognised internationally, and it is listed as a UNESCO World Heritage Area. The park is largely owned by the Aboriginal people of the area, the Bininj. It is leased by the Commonwealth of Australia and managed by Parks Australia North (PAN).

Uranium is mined within the catchment of Magela Creek, a tributary of the East Alligator River. The mining lease areas and nearby townsite of Jabiru have been excised from Kakadu National Park. Mining operations and provision of residential and urban services at Jabiru, together with recreational and tourist activities, have direct and indirect effects on the environmental values of the Park. However, management of mining, urban and tourist activities is intended to minimise any adverse impacts and maximise the opportunities to conserve the physical, biological and cultural heritage values. This has been pursued through a comprehensive research and monitoring program along the channel and floodplains of Magela Creek downstream of the Ranger uranium mine site at Jabiru East (Finlayson et al 1990, Humphrey et al 1995). The Environmental Research Institute of the Supervising Scientist independently, and in collaboration with other agencies, undertakes and promotes research relevant to the environmental effects of mining operations in the ARR and minimisation of these effects after decommissioning and rehabilitation. Although the coastal component of the research has focused on downstream effects of mining, much of the information gathered is applicable as a baseline to assess the effects of climatic and other changes on the catchment environment. It also provides a sound basis for comparison with other parts of the region.

Scientific research in the ARR commenced in the early 1970s with an Environmental Fact Finding Study (Christian & Aldrick 1977). Results of the study were used in assessment of the impact of mining and milling uranium ore, and by the Fox Inquiry (Fox et al 1977). Research has continued in the region to gain information for the management of the National Park. As a consequence of the history of research, information available for the wider region matches the breadth and detail of that for many coastal areas in Australia with a large urban population. However, important questions for management of the Region are

- is effective use being made of the information?
- is the information being converted to intelligence that supports effective and efficient management?

For coastal management to be most effective it is increasingly necessary to ensure dialogue and cooperation between the technical, scientific and management bodies, as well as between various government agencies and community groups that share responsibility for management. In this respect, the ways in which the Aboriginal people from the ARR are involved in the environmental management process for the region, through management of the National Park, may provide a working model for integrated coastal management elsewhere in the remote Wet-Dry tropics of Australia.

4 The climate change scenario

Climate is an abstract concept. It represents the summation of all interacting atmospheric processes and weather conditions affecting a locality. The climate changes under consideration in this context commonly refer to trends in climatic factors, such as CO_2 content of the atmosphere, temperature and rainfall. These changes occur at time scales up to 100 years and may be irreversible. Changes predicted to occur as a result of the 'greenhouse effect' provide examples of the type of variability to be considered in vulnerability assessment, although other fluctuations in climate may be equally important at this scale. Hence the natural variability of local climatic conditions should be examined as part of the vulnerability assessment process. McQuade et al (1996) have pointed out that the masking effects of natural climate variability make it unlikely that changes of the order suggested by global climate models will be confirmed for decades. The natural trends, oscillations and more random perturbations in climate need to be identified and distinguished from the 'exotic' changes caused by human populations

The major source of information for the prediction of potential climate change in the Northern Territory, and current scientific advice on the regional implications of that change, has been provided by Wasson (1992) and CSIRO (1994). The generalised best estimates and ranges, mainly for the year 2030 AD have been provided by CSIRO (1994). Unless greenhouse gas emissions are substantially reduced, the cumulative effect of increases in all greenhouse gases is expected to be equivalent to a doubling of pre-industrial concentrations of atmospheric CO_2 (NOAA 1992, CSIRO 1994). Climatic change is likely to be a continuing process from now until well beyond 2030, with superimposed interannual variations due to other natural effects such as solar activity and volcanic eruptions. Estimates are based on the Intergovernmental Panel on Climate Change (IPCC) Scientific Assessment and ongoing CSIRO research. Surprises, including rapid changes, are possible according to these sources. Potential future changes outlined by the CSIRO (1994) are summarised in table 1.

5 Predicted sea level rises

Sea level changes are related to global climate change (Warwick et al 1995); interannual variation in weather conditions, such as those related to ENSO events (Komar & Enfield

1987); as well as to hydro-isostatic (Chappell et al 1982) and tectonic (Woodroffe et al 1987) effects within van Diemen Gulf. Two scenarios for global sea level rise have been published. Initially, the IPCC (1990) scenarios were the main source of information for Australia. However, these are currently under revision and are due to be updated. More recently the IPCC (1990) scenarios have been replaced by the work of Wigley & Raper (1992). This has been adopted by the CSIRO (1994) and provides the basis for vulnerability assessment in the ARR. Global predictions of sea level rise range from 25 to 80 cm by the year 2100, with a best estimate of 50 cm. By the year 2030 sea level will have risen between 8 and 30 cm. The estimates are plus or minus 25% lower than the best estimate presented by the IPCC in 1990 (Warwick & Oerlemans 1990). They require further adjustment to allow for regional and site specific conditions to determine the relative sea level change at that place. Such predictions are not currently available for the ARR.

Long-term variations in climate and sea level, those occurring over hundreds of years to millennia, in the ARR have been established in geomorphologic and stratigraphic investigations for the Mary (Woodroffe & Mulrennan 1993) and South Alligator River systems (Hope et al 1985, Woodroffe et al 1985, 1986), the Magela Creek and coastal plains (Nanson et al 1990, Wasson 1992), and the Point Stuart chenier sequence (Clarke et al 1979, Lees 1987). General descriptions of landform evolution in the region have been provided by (Storey et al 1969, Christian & Aldrick 1977, Duggan 1985). These investigations provide a context for environmental changes currently occurring in the ARR and for the higher frequency changes that have occurred in the past 100 years and which may recur in the near future.

More recently, short-term fluctuations in sea level, those occurring within the historical period, have been examined by the National Tide Facility. The record is short, dating from 1959 to 1992, and based on tide gauge records from Darwin Harbour. It indicates that there may have been a slight variation in sea level in the region over the period of record, at rates between approximately 0.10 mm and 0.17 mm per year. However, there is a need for caution in interpreting the short record because the trend is very low. It may be biased by interannual variations in climate, such as those due to ENSO events, and it is located outside the ARR.

The record of annual mean sea levels for Darwin displays an interannual variability rising from approximately 3875 mm to 4125 mm over the 4 years from 1972 to 1975, and a relative fall to 1992 levels. The variation reasonably could be anticipated to affect coastal processes and tidal activity within the estuarine reaches of the rivers. However, the response rate of coastal and estuarine processes to such change is largely unknown. Responses of a sandy beach to sea level fluctuation are of the order of 1.0 m of shoreline retreat for each 1.0 cm of sea level rise (Bruun 1962, 1983) with the beach response lagging the peak sea level. Similar changes may be anticipated to occur on muddy coasts.

6 Environmental responses

Environmental responses to climate and sea level changes are manifested through hydrological, hydrodynamic, geomorphological and ecological processes. Development of the coastal plains also rests on a balance between these processes such that the coast progrades when sea levels are lowering, rainfall is high and fluvial forces prevail. Conversely, the shoreline retreats and tidal creeks extend landwards when sea level is rising, rainfall is low and coastal processes prevail. There is a wide range of interactions and responses between these extreme conditions. Hence an understanding of the coastal hydrodynamics, and particularly the hydrology of streams and wetlands, is a fundamental requirement for understanding the biological and chemical processes that characterise stream and wetland ecosystems. The complexities of the hydrological cycle for the ARR are not thoroughly understood, especially in relation to groundwater interactions with the aquatic and wetland ecosystems. Effective management practices for such aquatic ecosystems are often limited by an inadequate understanding of the underlying hydrological processes.

Although the Kakadu wetlands have undergone major ecological change over the past few decades (Finlayson 1990, Finlayson et al 1988) and controversy has surrounded plans by mining companies in the region to release excess runoff water to the aquatic ecosystem (Johnston 1991) this has not provided sufficient impetus to thoroughly investigate the complex hydrology of the region.

Adjacent to the ARR pastoralists have registered concerns over increasing encroachment of saline waters into freshwater wetlands that are used for seasonal pastures (Knighton et al 1991, 1992, Woodroffe & Mulrennan 1993). Remedial measures to deal with this problem have included emplacement of open mesh rubble mattresses and earth bunds to impede tide water penetration. The porosity of the mattresses and inherent instability of the bund walls brings these mitigation measures into question. More successful approaches to the problem will require an increased understanding of coastal and floodplain hydrodynamics and geomorphology that is based on rigorous, scientific research (Sessional Committee Northern Territory 1995.)

Ecological process affected by environmental change include the expansion and contraction of plant communities with consequent effects on animal habitats. Again, insufficient knowledge of the interaction between wetland plant communities and changes in hydrological and depositional conditions makes prediction of the long-term effects difficult. Wetland plant communities are viewed as being widespread in the region and highly dynamic in terms of variability in species composition, structure of the community and geographic spatial extent. The plant species are widespread at pan-regional and regional scales and no communities or individual species of rare or endangered species have been recorded. Similarly, animal species are widespread and no rare and endangered species are known from areas that could be affected by environmental change.

Environmental change is continuous. All physical, cultural, social and economic systems are changing. A key factor to be considered is whether change can be perceived as having adverse effects on natural and human systems. In this context, perception is important because it dictates the type of response taken to change. Heightened perception of change can result in increased activity to record and identify changes, and implement measures to deal with them. On the other hand, diminished perception of change can result in relaxation of measures previously used to address the negative effects of change. For instance, this latter situation is seen over successive years following extreme climatic events, such as tropical cyclones, wherein there are gradual cuts in budgets and reductions in resources to deal with potential but very real hazards. It is accompanied by a lowering of awareness of the implications that the events or changes can have in terms of hazards, risks and lifestyles of humans.

7 Management strategies and research

Bayliss et al (1998) pointed out that the floodplains of Kakadu National Park cannot be managed in isolation from the remainder of the region or, indeed, lands bordering on van Diemen Gulf. Environmental information from across the larger region is required in order to implement integrated coastal zone management. The wetlands of the region are already undergoing major ecological change and can be expected to change even further, especially in consideration of globally predicted climate change and sea level rise. Long-term monitoring of key biophysical parameters in the wetlands and adjacent seas are required for change to be assessed and appropriate management strategies implemented. This will require a spatial and temporal database that itself must be contained within an effective information management system. In many instances the management strategies will be aimed at rehabilitating degraded habitat, whether it includes control of weeds or alteration of the water regime or physical features of the wetlands. Management objectives can be targeted at specific problems, but they are unlikely to be effective in the long-term if carried out in isolation of adjacent linked areas.

In the context of wetland management throughout the region it is stressed, as argued above, that a holistic approach should be developed as it is not possible to manage the wetland systems in isolation. This point is made by Bayliss et al (1998) and Storrs & Finlayson (1997) who assessed the extent of biophysical interaction between wetland ecosystems. The adjacent areas of the East Alligator floodplain are not covered by a similar plan even though they share many of the same problems, as listed above. Further, Bayliss et al (1998) present a case for the integration of management effort for all lands bordering van Diemen Gulf (ie involving all tiers of government, land-holders and representative associations).

Effective management, including rehabilitation, of wetlands is, at least in part, dependent on access to an adequate information base. The necessity of both establishing and curating this information resource has been expounded by Bayliss et al (1998). Information and database systems that could be of value within the ARR could include: a meta-database to record basic information on the projects undertaken; a relational database to provide linkages between data sets and data types; and a spatial database for maps and imagery (Finlayson 1997). As with the management tasks themselves it is doubted that these databases will be truly effective if they are confined to jurisdictional boundaries. Given the ecological linkages that exist between the wetlands the information base can not be confined by lines on maps. Management processes that involve cooperation across these lines are occurring and are strongly encouraged.

In addition to utilising effective integrated decision making processes and information systems there is a need to implement well designed monitoring programs. The steps required for designing monitoring programs have been presented by Finlayson (1996). These are not repeated here except to emphasise the necessity of framing realistic objectives and linking these to hypotheses that can be tested with well chosen sampling regimes and analytical procedures.

8 Coastal monitoring node

The aim of the ARR vulnerability assessment project was to facilitate ongoing assessment of the coast, in particular the wetlands, to the effects of short-term changes in climate and other environmental factors that occur within planning horizons of approximately 100 years (Bayliss et al 1998). While the project focused on Kakadu National Park, and the floodplains of Magela Creek, its outcomes have wider application to the management of the ARR in general, as well as for floodplain environments elsewhere in the Wet-Dry tropics. Thus, the proposed monitoring node is being established with the purpose of establishing a monitoring approach with sufficient utility to be extended across the wetlands of the Wet-Dry tropics.

The aims of the coastal monitoring node are to

- Develop a regional capacity to measure and assess change on the floodplains and coast of Kakadu National Park, its catchment area, the wider ARR, and in the Wet-Dry tropics in general.
- Increase Australia's capacity in the monitoring of coastal change through establishment of a coordinated monitoring program which can function as a benchmark for monitoring in the Wet-Dry tropics and eventually in any low lying coastal areas subject to episodic flooding.
- Provide a regional and local benchmark against which to measure environmental changes in the Magela Creek system which could be attributed to mining and other human activities.

The operation of the node will meet the basic requirements of the Commonwealth Coastal Policy, namely the need to

- Ensure that the monitoring program addresses management questions.
- Coordinate Commonwealth information collection exercises and monitoring initiatives within the Commonwealth.

- Generate understanding, cooperation and support of the key players in coastal management of the region through involvement and ownership rather than centralised control.

Furthermore, there is a need to provide benchmarks, both nationally and internationally, from which to measure changes in Wet-Dry tropical environments. The ARR provides an excellent opportunity to do this as a result of its conservation and resource significance, its sound history of research and its considerable body of material that could be collated to provide baseline descriptions of the essential characteristics and attributes of change in this type of environment. The development of further expertise that would result from this proposal will be of national and international significance.

The initial components of establishing the monitoring node are

- Coordination and collation of existing data and information
- Development of a framework for monitoring of large scale change processes that shape the morphology of the floodplains.

These tasks are being addressed through a consultative process with other governmental agencies, research institutions and local community groups. The emphasis is on consultation and collaboration in order to address the needs of land managers and users in this highly variable and changing coastal environment.

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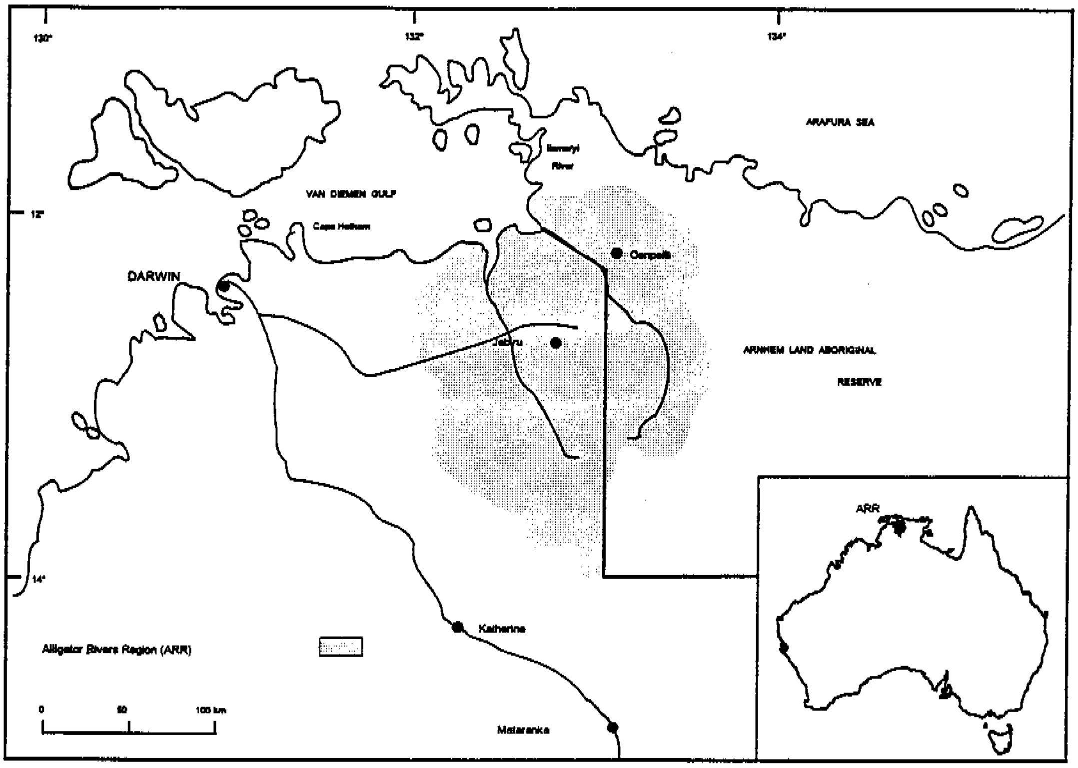

Map 1 The Biophysical Region

Table 1 Predictions of climate change (CSIRO 1994).

Temperature Global average warming to increase by 0.2–0.5°C per decade. Australia in 2030, relative to 1990, will be • 1–2°C warmer in northern coastal areas • 1–3°C warmer in southern coastal areas • 2–4°C warmer inland • even warmer in drier areas, and possibly less so in wetter areas
Rainfall Rainfall in Australia in 2030, relative to 1990 • large area average increase of 0–20% in summer in the summer rainfall region • monsoon more intense but monsoon trough not extending further south • less certain overall decrease of 0–20% in winter in the winter rainfall region • local changes could be two or three times larger due to topographic effects • general increase in rainfall intensities • possible marked increase in heavy rain events • longer dry spells in mid-latitudes
Extreme events Will change in magnitude and frequency more rapidly than the averages eg more very hot days, fewer frosts, more floods and dry spells.
Clouds Preliminary indication of an increase of 0–10% in total cloud cover in tropical Australia and a 0–15% decrease in the south of the continent.
Tropical cyclones Cyclones could travel further south and their preferred paths may alter but effects on intensity are uncertain. ENSO could affect both the location and frequency.
ENSO Future behaviour of the El Nino – Southern Oscillation events is uncertain. Probably El Ninos and anti-El Ninos will continue to occur, to produce drought and flood years.
Winds Stronger monsoon westerlies are expected in northern Australia and stronger winds will accompany severe weather. Mid-latitude westerlies are expected further south over Australia but change in the trade winds of the north are not yet clear.
Evaporation It is anticipated that there will be a 5–15% increase in potential evaporation by 2030.
Sea level Predicted changes in global sea level include • a global average rise of 3–10 cm per decade • a best estimate for Australia by 2030 AD is about 20 $\pm$ 10 cm above 1990 levels • local variations due to changes in weather and currents, affecting magnitude and frequency of extreme events such as storm surges, waves and estuarine flooding
Direct CO_2 effects CO_2 concentrations increase from 350 ppm in 1990 to 460 ppm with increased growth rates of C_3 plants (eg wheat and temperate grasses), but have less effect on C_4 plants (eg sorghum)

Major components of the Coastal Monitoring program in the Alligator Rivers Region

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Abstract

A Coastal Monitoring Node for assessing and monitoring environmental change in the Wet-Dry tropics is currently being established within the Environmental Research Institute of the Supervising Scientist (***eriss***). This node will develop a regional capacity to measure and assess change on the floodplains and coastline of Kakadu National Park, the wider Alligator Rivers Region, and the Wet-Dry tropics in general. The initial aim is to provide a survey and monitoring framework using a differential Global Positioning Systems to accurately georeference and store information, and provide baseline data.

Keywords: coastal monitoring, Wet-Dry tropics, management, differential Global Positioning System

1 Introduction

There are many important components that have been identified as integral parts of the coastal monitoring program; however the broad aim is to

- Provide a survey framework for georeferencing and mapping of all spatial information to be gathered in the coastal monitoring program in the Alligator Rivers Region (ARR), which contains Kakadu National Park.

As it is a large-scale time-consuming project, many smaller projects and tasks have been identified as necessary parts of the program. These are listed below in the recommended sequence of investigation (Finlayson et al, in prep):

- establish a Geographic Information System (GIS) structure for data collation, analysis and management;
- establish and adopt standards for georeferencing of all information to be gathered, particularly in the field by a differential Global Positioning System (differential GPS) and other means of referencing to known coordinates;
- acquire and deploy: (a) meteorologic, (b) oceanographic, and (c) river gauging equipment for fully automated recording of core environmental information;
- from available, vertical aerial photographs estimate historical shoreline movements along the coast and in the lower estuarine reaches of the rivers;
- establish key monitoring sites and initiate regular surveys of storm washover and shoreline movement;
- from available, vertical aerial photographs, assess historical changes to the tidal creeks of floodplains on the East and South Alligator River systems;

- from available, vertical aerial photographs estimate historical change in the distribution of mangroves along the coast and in the lower estuarine reaches of the rivers;
- initiate monitoring surveys of the species distribution and community structure of mangroves along the coast and in the lower estuarine reaches of the rivers;
- from available, vertical aerial photographs, determine historical changes in the distribution of salt-affected vegetation communities on the floodplains of the East and South Alligator Rivers;
- incorporate all spatial information and temporal descriptions in the Geographic Information System; and
- acquire bibliographic materials and collate information on data sets relating to integrated coastal zone management in the Wet-Dry tropics in a centralised metadatabase.

Two additional areas where work is required have recently been identified:
- document the history of land use and environmental change; and
- review the existing work (Woodroffe & Mulrennan 1993, Wasson 1992, etc) that has been done in the region with regard to stratigraphy and sediments.

Each of these projects and/or tasks initially require commitments of time and resources to determine what is known about each area of interest before proceeding with a monitoring strategy. Initially an information-gathering exercise is taking place to establish what work has been proposed, commenced or completed. This is being undertaken in consultation with various government departments, companies and organisations that hold relevant data and information, and are perhaps working in this area.

2 Project description and status

This section will provide a brief description of each of the projects listed above, provide the aim/s or rationale, the present status of the project and expected outcomes. The broad aim of the project – to establish a survey framework for georeferencing and mapping of spatial information – will be further discussed in Section 3.

2.1 Establishment of a GIS system at *eriss*

eriss is in the process of establishing a GIS system structure for data collation, analysis and management. The GIS will be used to store and analyse data from all ***eriss*** programs and in particular the Coastal Monitoring program. It is fundamental to have an effective strategy for data management and information storage, management and exchange for all projects undertaken in this program, and for the data management systems to be in place before projects are begun. The GIS will provide the framework and base data layers into which all new and collated information will reside.

The hardware and software is now in place and many of the base GIS layers are available for use. These include coastlines and other topographic data, administrative boundaries, vegetation and geological data and herbarium records. In the near future data will be available from the Parks Australia North GIS which includes a great deal of valuable data on firescar mapping in Kakadu National Park.

The Coastal Monitoring program is expected to make significant contributions of new data which will be combined with the existing data and analysed as required. Metadata entry into the Environmental Data Directory has commenced and through this process metadata will be available via the National Metadata Directory.

2.2 Georeferencing of spatial data using a differential GPS

The establishment of a differential GPS at ***eriss*** will provide the flexibility to establish reference sites within the ARR as they are required. It will also provide a survey framework for spatial differential GPS and develop ***eriss*** capacity to locate and map features such as saltwater intrusions, mangroves, wetland areas, cross-sections (both floodplain and channel), tidal creek extensions etc. With the location of these features accurately known, relocating these features for future research and study will be possible.

The following tasks have been identified as essential to the establishment of a georeferencing framework at ***eriss***:

- Relocate the AUSLIG (Australian Surveying and Land Information Group) GPS base station from Manton Dam to Jabiru Airport;
- Select and purchase suitable differential GPS equipment;
- Organise and administer staff training in use of the equipment, including procedures for downloading data to GIS;
- Relocate existing Benchmarks and Geodetic points;
- Establish field control points as projects are identified and implemented.

It has been agreed that the AUSLIG GPS base station should be moved from Manton Dam to Jabiru airport and the move should be completed during August 1997. ***eriss*** has also purchased an Ashtech differential GPS, which is directly compatible with the AUSLIG GPS equipment, and training in its use has commenced.

2.3 Establishing baseline information

Information is required for various environmental parameters, to determine a set of conditions that can be called baseline. This will effectively give us a starting point by which we can monitor and determine any changes that occur in the future. Examination of historical records could provide an indication where such changes have occurred and perhaps are ongoing, and point to sites where monitoring equipment could be located.

The location, costs and reliability of existing data sources and information are being investigated to determine the base line conditions for the following parameters within the ARR.

2.3.1 Meteorologic records

The aim is to establish a network of weather stations within the ARR (at a density to be determined) and surrounding regions, to collect, collate and analyse weather and climate information, enabling climatic variation within the ARR to be monitored. Climatic conditions for the ARR have been described by the Australian Bureau of Meteorology (1961), McAlpine (1969), Christian & Aldrick (1977), Woodroffe et al (1986), Nanson et al (1990), Riley (1991), Wasson (1992), Butterworth (1995) and McQuade et al (1996).

The following tasks have been identified for this project:

- Obtain locations of weather stations (operational and discontinued) and determine what instrumentation they have or had;
- Establish what data exists for each of the weather stations and its usefulness to the project;
- Determine the density of coverage required for a network of weather stations and establish where new stations should be located to complete full network coverage of the ARR.

The location of weather stations within the ARR and surrounds has been determined through consultation with Bureau of Meteorology (BOM) and the NT Power and Water Authority

(PAWA), Department of Lands, Planning and Environment (DLPE) Water Resources Division. The instrumentation at these sites is presently being ascertained.

Data collation problems with remote locations mean that weather stations may be telegraphic, automatic, radar or Doppler radar, and can be set up for specific research purposes, usually in collaboration with other bodies. This substantially increases the cost of establishing weather stations.

A fully automated weather station has just been purchased by ***eriss*** ($8000) to be located at Jabiru East for use in various projects. All equipment, sensors and probes will be compatible with BOM standards.

Once this information has been gathered the existing network can be determined and additional weather stations may be established as necessary, within financial constraints.

2.3.2 Oceanographic records

The immediate aim of the oceanographic monitoring project for the ARR is to design an atmospheric and oceanographic monitoring framework for van Diemen Gulf. The oceanographic processes operating within van Diemen Gulf may have considerable influence upon the hydrology of the ARR; hence tidal data may provide insight into the hydrology and circulation within both the Gulf and the ARR. It has been suggested that offshore circulation patterns are tide and wind-driven whilst long and short wave radiation causes inshore effects (D. Williams pers comm).

It is important to determine relationships between weather conditions, sea level fluctuation, water circulation and shoreline changes on the coast of the ARR, and to examine any relationships between sea level fluctuation and tidal water movement in the Wildman, South Alligator and East Alligator Rivers during low-flow conditions.

Unfortunately there are no tide gauges in van Diemen Gulf with Darwin Harbour (1/1/59 to present) and Melville Bay at Gove (9/5/80 to present) the closest, both operated by PAWA. There has been some work completed by PAWA with tide gauges, however these are relatively short projects in the vicinity of Chambers Bay, Mary River region. Processes in Van Diemen Gulf are complex, including oceanic processes and ENSO events, integrated with wind, tides, coastal and island geomorphology and bathymetry, which should all be part of the modelling process. A network of monitoring points (such as tide and weather stations) should be established around the Gulf to verify modelling. It may be possible to determine the circulation and current patterns in van Diemen Gulf using wind direction and velocity, therefore the location of weather stations that measure these parameters is also important to this project.

The following tasks have been identified:

- Investigate the oceanographic processes within van Diemen Gulf, beginning with a broad scale circulation model. More complex modelling should include wind, tidal and geomorphological influences affecting Gulf oceanography;
- Establish a network of monitoring points and tide stations around the Gulf to verify modelling;
- Investigate the worth of van Diemen Gulf as an indicator for predicting climate change in Australia.

This work is outside the scope of the present staffing at ***eriss*** and is likely to be carried out in collaboration with the University of Western Australia (UWA) and PAWA.

2.3.3 Hydrologic and river gauging records

The hydrological cycle of the ARR involves complex interactions between the atmosphere, the topography and the lithosphere. The ARR is drained by the South Alligator and East Alligator Rivers with the smaller West Alligator and Wildman Rivers draining the north-western portion of the region, all into van Diemen Gulf (figure 1). The Mary and Katherine Rivers drain a minor portion of the south-westerly part of the region. Much of the information on the hydrology of the region comes from Chartres et al (1991), Kingston (1991), Nanson et al (1990) and Roberts (1991), while McQuade et al (1996) suggests that the hydrology of the region is affected by three of the major physiographic land surface units: 1) the escarpment plateau; 2) the lowlands; and 3) the flood plains

The tasks that have been identified are:

- Obtain locations of gauging or water level recorders (operational and discontinued), and determine the length of recorded data and its usefulness and reliability;
- Determine if the operational gauging stations are sufficient to provide the knowledge of the hydrology, rainfall and storm patterns of the ARR that is required. If they are not, determine locations where new stations might be established and investigate recommissioning gauges that have been discontinued;
- Investigate whether the use of data from surrounding regions might be satisfactory ie carry out a regional hydrologic analysis.

The locations and lengths of record for existing and discontinued gauging stations have been established, however at this stage the analysis has not been started. The aim is to understand the hydrology of the ARR and determine its regional context.

2.3.4 Shoreline movement and storm surges

Changes in shoreline characteristics and surge overwash features can be identified from vertical aerial photographs taken since 1940, gaining information which can be utilised in other projects eg status and distribution of mangrove communities. Patterns of shoreline movement occurring between 1943 and 1989, in the vicinity of Tommycut Creek and Sampan Creek on the Lower Mary River Plains, have been reported by Knighton et al (1992) and Woodroffe & Mulrennan (1993). The Lower Mary River Plains are adjacent to Kakadu National Park, both meeting van Diemen Gulf to the north.

The tasks identified are:

- Utilise aerial photography taken intermittently since 1943 (for which coastline only is available) to determine whether the shoreline of the ARR is experiencing the same trends;
- Investigate availability, usefulness and cost of Landsat and spot imagery as well as other remotely sensed information;
- Attempt to scan photographs into GIS environment and rectify from common points;
- Locate key areas by differential GPS and determine any obvious changes.

Relevant aerial photography should also be acquired to complement the existing aerial photographs that ***eriss*** has already obtained (1943, 1950, 1991). This existing and any future aerial photography will require some form of ground truthing.

A map of the existing shoreline of ARR, as well as historical changes that might have occurred, will be produced. This will serve as the baseline and provide information as to where potential monitoring sites could be established. If possible future aerial photography should be flown on a regular basis.

2.3.5 Mangrove distributions and species identification

The aim of this part of the coastal monitoring node is to determine spatial variation in the structure and productivity of mangrove communities along the coastline, including the coastal margin and lower estuarine reaches, in Kakadu National Park and the wider ARR.

In the vicinity of the ARR, Woodroffe & Mulrennan (1993) documented dramatic recent changes to the Lower Mary River floodplain, with salt water intrusion and upstream expansion of the tidal creek network. This has caused death of freshwater wetland communities with loss of 60 km^2 of *Melaleuca* forest, and upstream invasion of mangroves. There are a number of potential causes including shoreline retreat, salt water intrusion and sea level rise. There is therefore considerable overlap with the shoreline retreat and salt water intrusion sub-projects of the Coastal Monitoring program.

The main tasks identified are:

- Utilise aerial photography to determine present and past extent of mangroves as described in section 2.3.4; similarly utilise satellite imagery and georeferencing with the differential GPS.
- Collaborate with Darwin Harbour mangroves projects where possible, crossing jurisdictional boundaries only by invitation.

As mentioned in section 2.3.4 some of the relevant aerial photography has been purchased and it is envisaged that the project will be a collaboration with the Australian Institute of Marine Science and the Parks and Wildlife Commission of the Northern Territory. The expected outcomes are similar to those of shoreline retreat as there is considerable overlap in the methodologies.

2.3.6 Salt flats and saline intrusion

The aim of this part of the Coastal Monitoring program is to determine past and potential changes in salt flat distribution and abundance. This will involve mapping the current extent of salt flats, providing a basic description of the type of salt flats present, and determining the status of data – what historic data exists at present and what will be required in order to monitor changes in distribution and ecological character of salt flats of the ARR, including Kakadu National Park.

Changes in salt flats in the vicinity of the ARR have been suggested by Woodroffe & Mulrennan (1993), with documentation of dramatic recent changes to the lower Mary River floodplain, including salt water intrusion and upstream expansion of the tidal creek network. There are a number of possible reasons for these events, including relative sea-level rise (Woodroffe 1995). Extension of tidal creeks and mangrove development has occurred on river systems within Kakadu National Park (Woodroffe 1995). Clark & Guppy (1988) showed that sea-level rise of 0.5–1.0 m would convert the Alligator Rivers freshwater wetlands to the large mangrove swamp that existed during the mid Holocene.

The tasks required for this part of the project are very similar to those outlined in sections 2.3.4 and 2.3.5, with the addition of

- Establishing markers to monitor rate of tree loss in combination with remotely sensed data;
- Examining techniques for measurement of soil salinity.

Several sub-projects have been identified:

- An initial survey of salt water intrusion into *Melaleuca* forest has been carried out by ***eriss*** and 3 sites selected.

- Kath Lynch (Northern Territory University) is completing an Honours project on salt tolerance of *Melaleuca* spp and provenances; responses in germination, growth and other physiological parameters.
- Stephanie Cobb (University of Western Australia) is an Honours student studying channel extension and geomorphology of tidal creeks and salt flats in Kakadu National Park.

On the completion of these projects there will be greater understanding of the salt flats and associated geomorphic and biologic features in the ARR, which will serve as a base line for future monitoring.

2.3.7 History of land use and environmental change

The history of land use affects current uses and provides baseline information for monitoring. Historical events and records can shed light upon the nature of the landscape prior to extensive non-Aboriginal land use in a region, assisting researchers and land managers to differentiate between natural and artificial change, and determine management priorities. When investigating environmental change, it is immediately a challenge to separate perceived from actual change. However, perceptions of change within the living memory of local people can serve as a guide to further investigation and research. This project gathers information on land use and environmental change from diverse sources, oral and written, with the aim of establishing a data registry of land use information. The project will also identify processes for a comprehensive historical analysis of this information. Current management issues may then be addressed with greater understanding of their history and more comprehensive baseline information available.

The tasks identified are:

- Carry out a literature review using metadata and other sources of information of land use changes in the region, including an analysis of the underlying reasons for such changes
- Identify and liaise with key contacts within agencies and/or associations and/or individuals holding unpublished information on land use changes
- Initiate a review of and document information on key organisations, including non-governmental groups and local community associations, involved in land use practices and management
- Obtain information on major changes in land use and store in an appropriately designed data registry
- Document and describe the extent of selected changes in land use, such as the presence and management of buffalo and extent of selected weed species
- Review the operations and management processes of the Lower Mary River Landcare Group.

The expected outcomes include

- Analyses of major historical changes in land uses from both written and oral sources
- Analyses of management structures and their effectiveness in addressing changes in the coastal environment, including community involvement and inter-sectoral interaction.

2.3.8 Sediments and stratigraphy

Long-term variations in climate and sea level, those occurring over hundreds of years to millennia, in the ARR have been established in geomorphologic and stratigraphic investigations. These have been completed for the Mary (Woodroffe & Mulrennan 1993) and South Alligator River systems (Hope et al 1985; Woodroffe et al 1985a, 1985b, 1986), the

Magela Creek and coastal plains (Nanson et al 1990; Wasson 1992), and the Point Stuart chenier sequence (Clarke et al 1979; Lees 1987).

There is a need to review this work to determine whether additional work is required. For example, there is little mention in the literature of geomorphic and stratigraphic investigations undertaken and completed on the East Alligator River.

Several tasks have been identified:

- Review existing work and determine if additional work is required
- Address the apparent absence of sediment study with regard to floodplain stability and its relationship with tidal and stream sedimentation patterns.

Work is yet to begin on this aspect of the Coastal Monitoring program.

2.3.9 Remote sensing and landscape change

Remote sensing techniques will be used to determine the extent and character of wetlands in northern Australia, and to evaluate the effectiveness of remote sensing techniques in monitoring coastal processes and change.

Remote sensing is cost effective and perhaps the only feasible way to monitor wetlands in the Wet-Dry tropics of Australia. In conjunction with the development of the GIS, ***eriss*** is collaborating with several organisations with expertise in remote sensing.

The following projects are underway:

- Preliminary investigation of saline intrusion in the Point Farewell area using Landsat TM (***eriss*** and the Northern Territory University Centre for Tropical Wetland Management)
- Investigation into the spread of *Mimosa pigra* in test areas using Landsat TM (***eriss*** and the Northern Territory University Centre for Tropical Wetland Management)
- Identifying and monitoring change in wetland inundation and vegetation patterns in the ARR using RADARSAT data (***eriss*** and the University of New South Wales)
- AIRSAR data is also being acquired for the coastal areas between the East and South Alligator Rivers and will be used for several Northern Territory University student projects to investigate its usefulness in the region.

The role of ***eriss*** in these projects is mainly to carry out fieldwork and to store and use the products of the remote sensing projects in the GIS for these and other projects.

3 Monitoring framework for georeferencing in the Alligator Rivers Region

A wide variety of field survey and monitoring programs are undertaken in the ARR. Generally these are conducted as stand alone surveys. If the surveys are to be linked for comparative or other purposes, they need to use a common standard for georeferencing purposes. Hence, the aim of the Coastal Monitoring program is to provide a survey framework for georeferencing and mapping of all spatial information. This will be done by ***eriss*** in collaboration with the Department of the Environment, Sport and Territories (DEST) and the Australian Surveying and Land Information Group (AUSLIG).

3.1 Objectives

1. The survey framework and procedures for georeferencing will be achieved by developing a capacity for differential GPS survey for spatial biophysical monitoring and field

assessment surveys within ***eriss***. Field observers at ***eriss*** will then use mobile, single and dual frequency GPS receivers standardised with an AUSLIG GPS base station to be located at Jabiru airport;
2. relocate existing survey benchmarks (BM) on and adjacent to the floodplains within Kakadu National Park;
3. Select and establish new survey benchmarks;
4. Use the existing and new benchmarks together with the AUSLIG base station, to provide differential GPS control for kinematic mapping and position fixing in the field;
5. Link all survey information in the ESRI (Australia) ARC/INFO Geographic Information System for spatial analysis and display.

3.2 Background

The hand-held GPS uaually provides locational accuracy of 50 to 100m. This might be reasonable for bushwalking or locating a distinctive feature in the field but is not acceptable when accurate mapping of features such as mangrove distributions, tidal extension of creeks etc is required. If greater accuracy is required then a differential GPS might be used.

3.2.1 Global Positioning Systems (GPS)

GPS collect signals from satellites orbiting the earth to determine positions on the ground and in the air. A minimum of three of the 24 satellites that continuously orbit the earth are required to accurately determine a position. The satellites are owned and positioned in orbit by the US Department of Defence to provide world-wide, continuous all-weather information on the user's location. Accuracy varies from a sub-centimetre level to within 100 metres depending on how the signals are collected and processed. Rodgers et al (1996) say that GPS satellites emit two signals: 1) a high precision "P-code" that provides centimetre accuracy, reserved for the military, and 2) a C/A code that allows 25m accuracy for civilian applications. The use of a reference receiver at a known or surveyed location can reduce the errors to obtain horizontal accuracy better than 5m. With highly sophisticated GPS equipment, accuracy in the order of a few centimetres can be achieved. This system is called a differential GPS.

Differential GPS is a data collection and processing technique in which two or more receivers track the same satellites simultaneously. One receiver is located over a known reference point (such as a BM) and the position of an unknown point is determined relative to the reference point (Morton et al 1993). ***eriss*** has recently purchased a differential GPS, comprising of a dual frequency receiver to be set up over known locations and a single frequency receiver to be used as the *Rover* or mapping receiver.

3.2.2 Survey base stations

AUSLIG has a network of 14 GPS base stations around Australia and Antarctica, taking readings at 3 minute intervals. The sites are geologically stable and have an estimated accuracy of 0.01 parts per million. The closest GPS base station to the ARR was at Manton Dam (60 km south of Darwin) until August, 1997, when AUSLIG relocated it to Jabiru airport. This move is expected to increase the accuracy (twofold) of any differential GPS used in the ARR. Figures quoted by AUSLIG and supply companies such as SAGEM suggest that accuracy of $\pm$ 30 mm in the horizontal and $\pm$ 50 mm in the vertical will be achievable.

3.2.3 Existing survey benchmarks

Survey benchmarks have been installed throughout Australia, including the ARR, and incorporated into the Australian Geodetic Survey Database. They provide a broad grid

(figure 2) from which a more detailed survey framework can be constructed by differential GPS and established by monumentation in the field.
An AUSLIG search of the Geodetic Database, between the Latitudes -13.0 and -12.0 and Longitudes 132.0 and 133.0 found 15 stations within the ARR.

3.3 Tasks

The establishment of differential GPS at ***eriss*** will provide flexibility in establishing reference sites as they are required. It will also provide a survey framework for spatial differential GPS and develop ***eriss*** capacity to locate and map features such as saltwater intrusions, mangroves, wetland areas, cross-sections, tidal creek extensions etc.

The following tasks were identified as essential to the establishment of a georeferencing framework at ***eriss***:

- The relocation AUSLIG GPS base station from Manton Dam to Jabiru Airport was considered essential to obtain the required centimetre accuracy. The site should be operational as an AUSLIG GPS base station by the end of August 1997.
- Ashtech differential GPS equipment was selected and purchased after discussions with AUSLIG to ensure that there is easy compatibility between data obtained at the base station and the field data. The equipment has arrived and relevant staff are undergoing training in its use. In the course of training, several of the streets in Jabiru have been mapped with the single frequency receiver mounted on a vehicle.
- The relocation of existing Benchmarks and Geodetic points within the ARR will take place in the next couple of months to begin establishing a grid of known sites throughout the region. The route taken to reach these benchmarks will be mapped using the differential GPS, imported into a GIS and annotated with road names and significant landmarks. Government departments, agencies and companies such as AUSLIG, NT Department of Lands, Planning and Environment, Jabiru Town Council and ERA Ranger Uranium Mine were contacted to determine the existence of benchmarks.

The establishment of field control points will be completed as projects are implemented. The following points need to be addressed:

- Site selection and stability – when selecting sites for the location of field reference control stations, it is important that the sites are within 10–20 kilometres of the proposed study sites and located on stable ground. Examination of aerial photographs and field inspections are required before field control sites are installed.
- Costs and equipment required to establish field control stations – temporary field control stations can be established using a power drill with masonry bits and coach bolts. The coach bolts will be hammered into the rocks, painted and then the antenna can be placed on a tripod at a known height over the coach bolt. A tripod with a 5/8 whitworth thread needs to be purchased. A post hole digger, concrete mixer, generators, appropriate vehicles and tools (wheelbarrow, shovels, trowels etc) are available. Other costs such as cement, steel reinforcing, PVC pipe etc are ongoing.
- Estimated time to establish each type of remote field control station is: temporary – 0.5 days, 2 people; permanent – 3 days, 2 people.

4 Conclusion

The establishment of differential GPS at ***eriss*** will enable geomorphic, biological features etc to be accurately mapped and located within the ARR. The ability to georeference such features will be a valuable tool within the frame work of future coastal monitoring in the region. The AUSLIG base station will be in operation by August 1997 and Ashtech differential GPS equipment has been purchased. Fieldwork using the differential GPS is programmed for September 1997.

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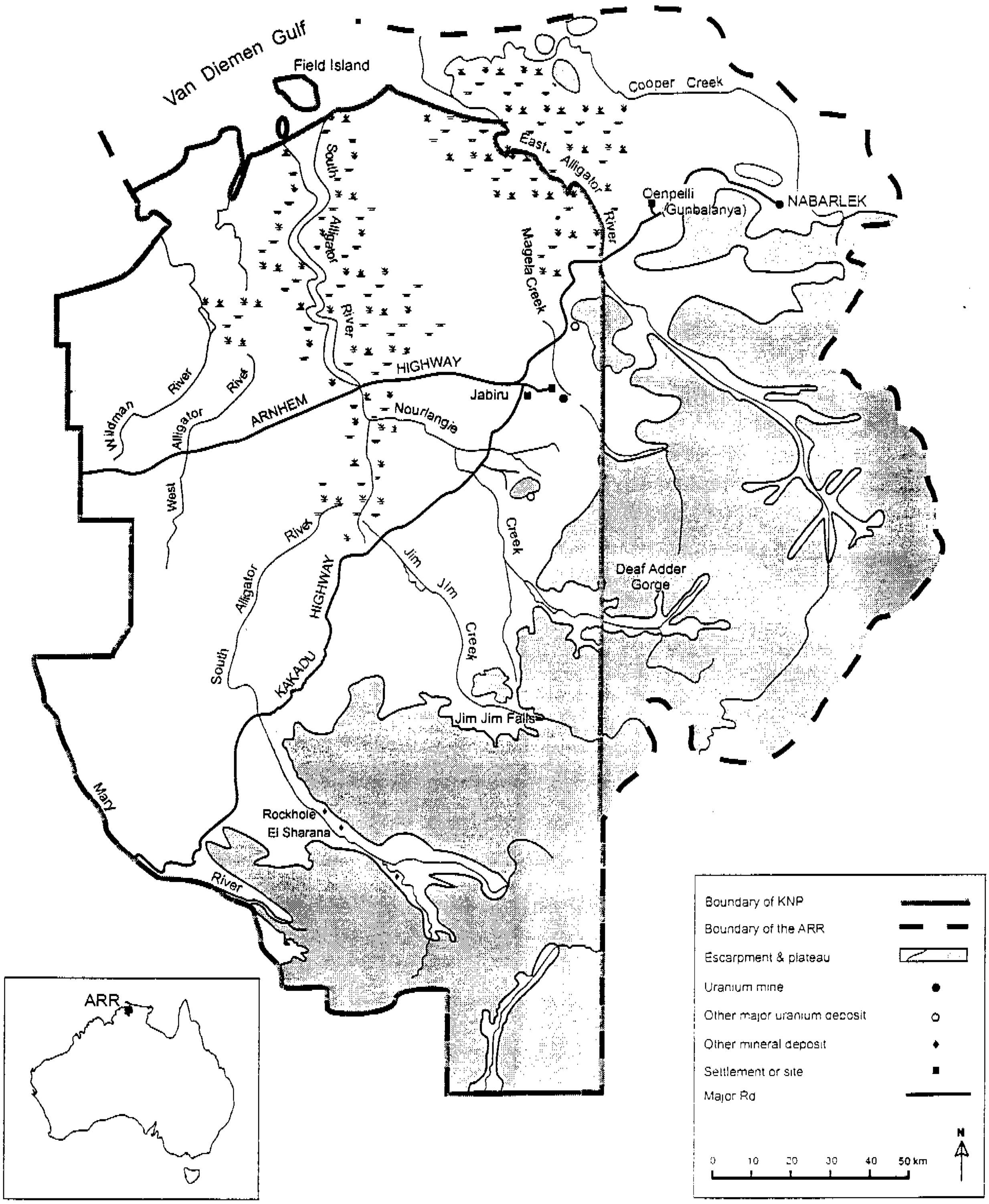

Figure 1: Drainage networks of the ARR

Benchmarks - ARR

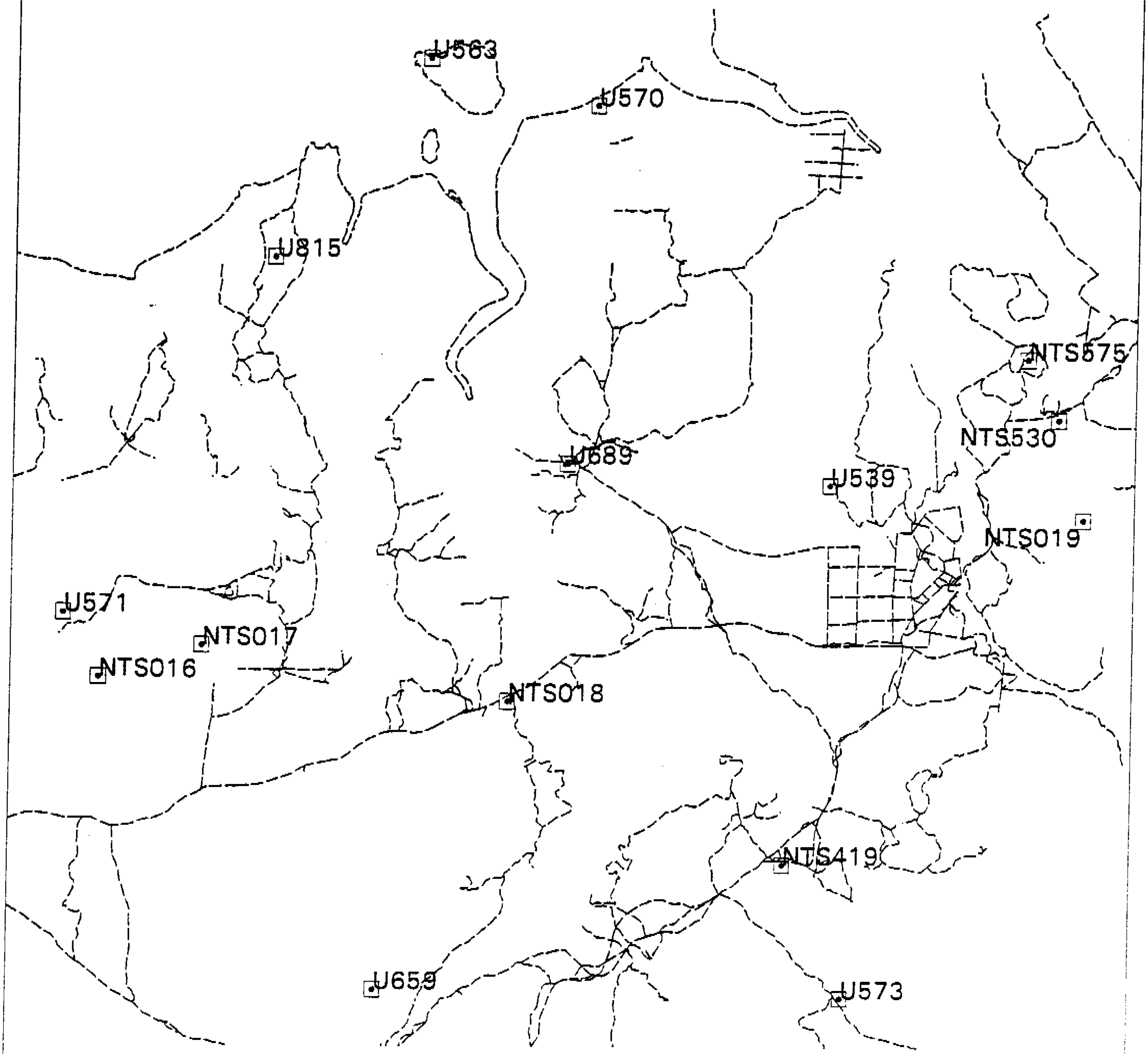

Figure 2: Location of Benchmarks on the north of Kakadu National Park between the Latitudes -13.0 and -12.0 and Longitudes 132.0 and 133.0

Framework for designing a monitoring program

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Abstract

A framework for assisting with the design of ideal and effective monitoring programs is presented. The framework is placed within the context of a management system that provides the means of responding to the results of the monitoring program. It is noted that monitoring is not the same as surveillance which is generally undertaken without a particular reason for collecting the data or information. The framework is not a prescriptive recipe for any particular monitoring program. It is a series of steps in a logical sequence. The general headings for these steps are listed below:

- Identify the problem or issue
- Set the objective
- Establish the hypothesis
- Choose the methods and variables
- Assess the feasibility and cost effectiveness
- Conduct a pilot study
- Collect the samples
- Sample analysis
- Analyse the samples
- Report the results
- Evaluate the project.

These steps are presented pictorially and described in the text. Feedback loops within the framework provide the means of reassessing the effectiveness of the preferred method in achieving the objective.

Keywords: monitoring, framework, feasibility, pilot study, sampling, analysis, feedback

1 Introduction

Environmental monitoring has received more and more attention in recent years. At a global level this has arisen as awareness of the extent of environmental degradation and habitat loss has increased. Wetlands, including those of northern Australia, have not been exempt from this general and widescale degradation (Finlayson & von Oertzen 1993, Storrs & Finlayson 1997, Finlayson et al 1998). Such is the concern at the extent of wetland degradation that increased effort is being directed towards developing effective management processes and responses to problems. In many instances this effort is being held back by a lack of relevant information on the nature of the problem, the cause of the problem and the effectiveness of management procedures and actions. Effective monitoring programs can help overcome such problems.

In a general sense monitoring addresses the general issue of change or lack of change through time and at particular places. Monitoring is built upon survey and surveillance but is more precise and oriented to specific targets or goals (Hellawell 1991).

Survey *is an exercise in which a set of qualitative observations are made but without any preconception of what the findings ought to be.*

Surveillance *is a time series of surveys to ascertain the extent of variability and/or range of values for particular parameters.*

Monitoring *is based on surveillance and is the systematic collection of data or information over time in order to ascertain the extent of compliance with a predetermined standard or position.*

Thus, monitoring is built on a time series of surveys and differs from surveillance by assuming that there is a specific reason for collecting the data or information (see Spellerberg 1991, Hellawell 1991, Furness et al 1994).

A framework for assisting with the design of a monitoring program is presented, largely based on that developed for the MedWet Mediterranean wetland program (Finlayson 1996a) and the Ramsar International Wetland Convention (Finlayson 1996b). The framework applies to all forms of monitoring (eg changes in the area of a wetland, the ecological health of a wetland, or the underlying reasons behind the loss of wetlands). It is not prescriptive and it is not a recipe for a particular type of problem or a particular type of wetland. It presents a series of steps that will assist those charged with designing a monitoring program to make decisions suitable for their own situation. A person using the framework will make these decisions based on some degree of knowledge and/or expertise. The framework is not a substitute for knowledge or expertise.

Where monitoring programs already exist the framework can be used to ensure that the monitoring is being done in a logical and well structured manner. All monitoring programs should be regularly reassessed and, where necessary, modified or even terminated.

2 Management and monitoring

Even a well designed monitoring program could have little value if the information that is collected is not utilised or does not influence the management process for that locality or site. Ideally, the locality or site will be subject to an interactive and holistic management plan that provides the means of responding to the information obtained from the monitoring program. If a formal or official management plan does not exist or is not being effectively implemented it is critical that mechanisms to make use of the information collected from a monitoring program are identified and developed.

Constable (1991) outlines the connection between a formal management procedure and an environmental monitoring program. Essentially, monitoring provides the means of measuring the output of the management procedure – that is, it provides the means of measuring the (observed) state of the environment and the extent to which it may have been altered. If the management objectives are not being met the existing legislation or regulations that affect the site (or location) are used to adjust the management activities. Importantly, a monitoring program can be established either before or after a particular management activity is implemented.

3 A framework for monitoring

Monitoring programs that are data rich and information poor are not effective management tools. Effectiveness is further reduced if the program provides misleading information. Frameworks for designing monitoring programs are tools to assist managers and planners. It is important to reiterate that the framework does not provide the answers – those responsible for the design provide the answers.

In an ideal situation the development of a monitoring program should be a straightforward and cooperative process between managers (who make decisions) and scientists (who provide expert advice and interpret data). In a simple sense, the managers would outline the need for a monitoring program and the scientists recommend the most appropriate techniques and, by an iterative process, an approach that has both scientific rigour and meets the management objectives will be developed. Adherence to a logical framework for designing monitoring programs cannot eliminate situations where this does not occur, but it can provide the means to identify the limits of a program and thereby potentially reduce the incidence of such cases.

The framework presented by Finlayson (1996 a, b) is shown in figure 1. Key aspects of the various components of the framework are described below, based on material presented in a number of published sources (Green 1984, Maher & Norris 1990, Goldsmith 1991, Spellerberg 1991, Finlayson 1994, Maher et al 1994). A summary of the points to consider when using the framework is given in table 1.

The framework illustrates an ideal and perhaps even a hypothetical situation. The amount of time spent considering each step in the framework will be dependent on time and resources. As the framework is not prescriptive there is no expectation that every step should be given equal attention. Managers and designers will make their own decisions based on local circumstances – the framework provides a guide to assist them in making these decisions.

3.1 Identify the problem or issue

Identification of the issue that leads to a change in the ecological character of a wetland is an important first step. This needs to be done clearly and unambiguously. It is also linked with setting the objective. Once this has been done it is possible to formulate management activities, including further investigations, to shed light on the issue/problem and to provide the justification for monitoring.

Where possible, the extent or scale of the problem (or likely problem) should also be identified (eg will the entire wetland or a number of different wetlands be affected?). Knowing the likely extent of the problem could be made difficult unless the ecological character of the wetland has been adequately described (eg how large is the wetland and how much water does it contain?). Thus, baseline or reference data are needed.

The cause (or most likely cause) of the problem should also be identified (eg nutrients added to an inflowing stream, or over-exploitation of a fish species). If the cause is not known an investigative program should be implemented, but it is noted that it can be difficult to establish cause-and-effect relationships between an activity and observed features of the environment. Often such information is not available and given the urgency of many situations little effort is made to obtain it. However, without such information it can be difficult to determine what should be monitored.

3.2 Set the objective

The objective provides the basis for collecting the information. Imprecise or inadequate objectives negate the usefulness of a monitoring program. Simply stating that an excessive level of water extraction should not occur is insufficient. The objective must be precise and specific. A surveillance program can occur without a specific objective, but a monitoring program cannot; the objective is the starting point of a monitoring program. When more than one objective is identified they should be prioritised in order to make the best use of time and resources.

Explicit statements not only assist in defining the sampling program, but in a long-term program also enable new staff to continue the work in a consistent manner. The objective provides the basis for obtaining the required information over a specified time period.

3.3 Establish the hypothesis

The objective is supported by an explicit hypothesis. A hypothesis that asserts to simply 'assess significant change' is not explicit and should be altered to indicate the required level of change (ie it exceeds a preset level or standard or differs from the long-term mean value by more than a specified level of statistical significance). In other words, a hypothesis that can be tested on the basis of the collected data or information is required. If this is not done it is not possible to know whether the objective has been attained. When determining whether or not a hypothesis has been supported by the data/information the sources and extent of variability in the data/information must also be recorded. This is particularly important when the natural fluctuations (eg in water depth or population levels) are highly variable or even unknown. The hypothesis should be based on sound information.

Hypotheses are often not formulated. Hypothesis-free monitoring has rarely been successful or cost-effective. Surveillance is generally done without formulating a hypothesis and can be useful, but may not provide evidence of the vital linkage between cause and effect that is necessary for management purposes. The significance of the results must be assessed if the program is to be useful for management actions.

3.4 Choose the methods and variables

Many monitoring methods are available. When assessing which method (or methods) are appropriate for monitoring a specific problem or site it is necessary to be aware of the advantages and disadvantages of the alternatives in relation to the level of protection that is required. A literature review and expert advice are essential. Above all, the monitoring objective and hypothesis need to be kept in mind; can the method detect change at the required level and over the chosen time period?

In choosing methods and/or variables it is necessary to know what level of change is acceptable (the hypothesis) and whether the preferred method can account for potential sources of variability in the data or information being collected. The following parameters need to be considered when deciding which method to use:

- existence and adequacy of baseline information
- general approaches for collecting data/information
- number and location of sampling sites
- sampling frequency

- sample replication
- specific techniques for collecting the samples
- techniques for processing and/or storing samples
- protocols and means of storing the data or information
- methods of statistically analysing the data
- processes for interpreting the data and information

In a general sense, the method needs to be able to detect the presence of any change, provide a basis for assessing the significance of the change and identify or clarify the cause.

Where an adequate method does not exist, well directed research is needed to develop or identify a specific technique. Methods that do not allow the hypothesis to be assessed should not be used.

3.5 Assess the feasibility and cost effectiveness

Once a method has been chosen and a sampling regime identified it is necessary to determine whether or not it is actually feasible to undertake the program on a regular and continual basis. Thus, factors that influence the sampling process and continuity of the program need to be considered, for example:

- availability of trained personnel to collect and process the samples
- access to sampling sites
- availability and reliability of specialist equipment for sample collection or analysis of samples
- means of analysing and interpreting the data
- usefulness of the data and information derived from it
- means of reporting in a timely manner
- financial and material support for continuing the program

If the monitoring program is contained within a structured management plan these factors should be easily assessed. If it is not contained within such a plan the assessment may be more difficult; great care should therefore be exercised.

In undertaking the feasibility assessment the cost effectiveness needs to be considered. The aim of a sampling program is to collect useful data or information with the least cost. The costs of data acquisition and analysis should be determined and considered in terms of the budget and the objective of the program. This assessment could benefit from independent and expert advice. Ideally, the cost effectiveness assessment would influence the budget allocation for the program. If an adequate budget is not available the program may need to be reduced or even abandoned. Inadequate funding should not be used as a reason to reduce the scientific rigour of a program. The goal is to obtain valid data for management purposes or to influence management decisions.

3.6 Conduct a pilot study

Before launching a large scale program a pilot study is essential in order to save time and resources in the future. This is the time to fine-tune the method and individual protocols and test the basic assumptions behind the method and sampling regime. Some idea of the rigour of the method and the need to make changes in the design or particular techniques for collecting or analysing the data can be obtained at this stage. This is the time to make changes to the procedures that have been chosen. It can be very expensive and even nullify a program if changes are made at a later date. Specialist field equipment should be tested in the pilot study and, if necessary, modified based on practical experience. It is also the opportunity to assess the training needs for staff involved.

The means of analysing the data also require testing. If statistical analyses are being used they should be tested with data from the pilot study. For example, possible violations of statistical assumptions such as non-normally distributed data, non-independent data, and insufficient replication should be established and compensatory action taken. It may not be important that all statistical assumptions are met exactly, but the importance and consequences of any violations should be understood.

The amount of time and effort required to conduct the pilot study will vary considerably depending on the hypothesis to be tested and the methods. In some instances the information collected during the pilot study can also be used as part of the monitoring information. Based on the assessment of the monitoring method in the pilot study the sampling regime should be confirmed and clearly articulated. Individual sampling protocols need to be finalised and a detailed procedure made available to all personnel involved. Standardisation between individuals can be critical. Information gained from the pilot study could be used to change both the hypothesis and the methods.

3.7 Collect the samples

Sampling should not commence before the method has been established and staff trained or instructed accordingly. The rigour with which sampling is undertaken can influence the success or otherwise of the monitoring program. Sampling details (eg replication, dimensions) should be based on statistical premises and checked during the pilot study. The agreed sampling protocols should be adhered to. Where this is not possible all variations should be carefully documented and this documentation kept with the data. The following documentation should accompany all samples:

- date and location
- names of sampling staff
- method used to collect the samples
- number of samples required
- equipment used to collect the samples
- methods used for sample storage or transport
- all changes to the established methods or protocols

Sampling and data collection should be done in a manner to ensure the results can be used with confidence (ie were adequately replicated). Documentation of all practices is a vital part of demonstrating this confidence.

The effectiveness of a monitoring program is also dependent on the timely processing of samples collected for further analysis (eg dissecting fish for chemical analysis of specific biological tissue). However, the need for rapid results should not compromise the processing of samples. If the processing is not sufficiently rapid the program may need reassessment.

Delays in processing the samples could also negate the usefulness of the program. When the samples are processed the following should be documented:

- date and location
- names of processing staff
- method used to process the samples
- equipment used to process the samples
- all changes to the established methods or protocols.

3.8 Analyse the samples

Many samples require analysis after they have been collected and processed. Whether this involves chemical analysis or biological identification the means of having this done should be determined in the pilot study.

Statistical analysis is regularly used to analyse data and ascertain the extent of any change or variation. These techniques should also be well and truly tested in the pilot study. There seems to be little point in collecting and processing samples if the means of interpreting the data are not available. Collecting samples in the hope of finding the means to analyse them is not an effective strategy for a monitoring program (it may be appropriate for a surveillance project). Achieving the objective of a monitoring program is not possible unless the data from the samples is made available for interpretation. Valid statistical analysis is critical where complicated or contentious issues are being addressed (see Hewett 1986, Bishop 1983). Sample and data analysis should be done by rigorous and valid processes.

As with sample collection a basic set of information should be documented when the samples are analysed:

- date and location
- names of analytical staff
- methods used for analysis
- equipment used for analysis
- means and location of storing data
- all changes to the established methods
- statistical tests and significance levels

3.9 Interpret data and report the results

All monitoring information and results need to be interpreted and reported in a timely and cost effective manner. If this is not done the program can be considered to have failed – monitoring is designed to provide results to assist further management. The interpretation should take place within the framework provided by the program objective. Making the reporting schedule and the reports themselves publicly available is one way of ensuring that this critical aspect of the monitoring program is given due attention.

Reporting can take many forms and it is not always necessary or even desirable to include all the results and detail, although these should be readily accessible. The form of the report will, in part, be determined by the nature of the problem and the monitoring objectives. Its express purpose is to ensure the monitoring data becomes part of the management planning process.

In many instances it will also be useful to comment on the need for further monitoring of the same nature or even of a different nature. The size and style of a report will vary according to the objective, the method used and the audience. Despite this variation in style the report should be succinct and concise and supported by statistical analyses.

The report should indicate whether or not the hypothesis has been supported and whether management action is required. It should also be used to assess the effectiveness of the sampling methods.

3.10 Evaluate the project

The framework given in table 1 and figure 1 provide a series of steps that feedback into the planning process. Throughout the planning and implementation process for a monitoring program these feedback steps should be used to ensure that the required rigour is being obtained and that the hypothesis can be tested by the data being collected. At the end of the program, or after a predetermined time period the entire process should be re-examined and necessary modifications made and recorded. Where the objectives have been met the program can be terminated.

4 Concluding comment

Monitoring is an integral component of the management process. Poorly designed monitoring programs are a liability and should be terminated and replaced as they can produce misleading and erroneous data or information. Given the difficulties of finding resources for management we do not need these to be wasted on ineffective monitoring.

The framework given above does not attempt to provide a recipe for any particular monitoring program. Rather, it provides a series of steps to assist people planning monitoring programs to make informed decisions about their particular needs. The feedback links in the framework are a means of ensuring that the adequacy of any program is regularly reassessed.

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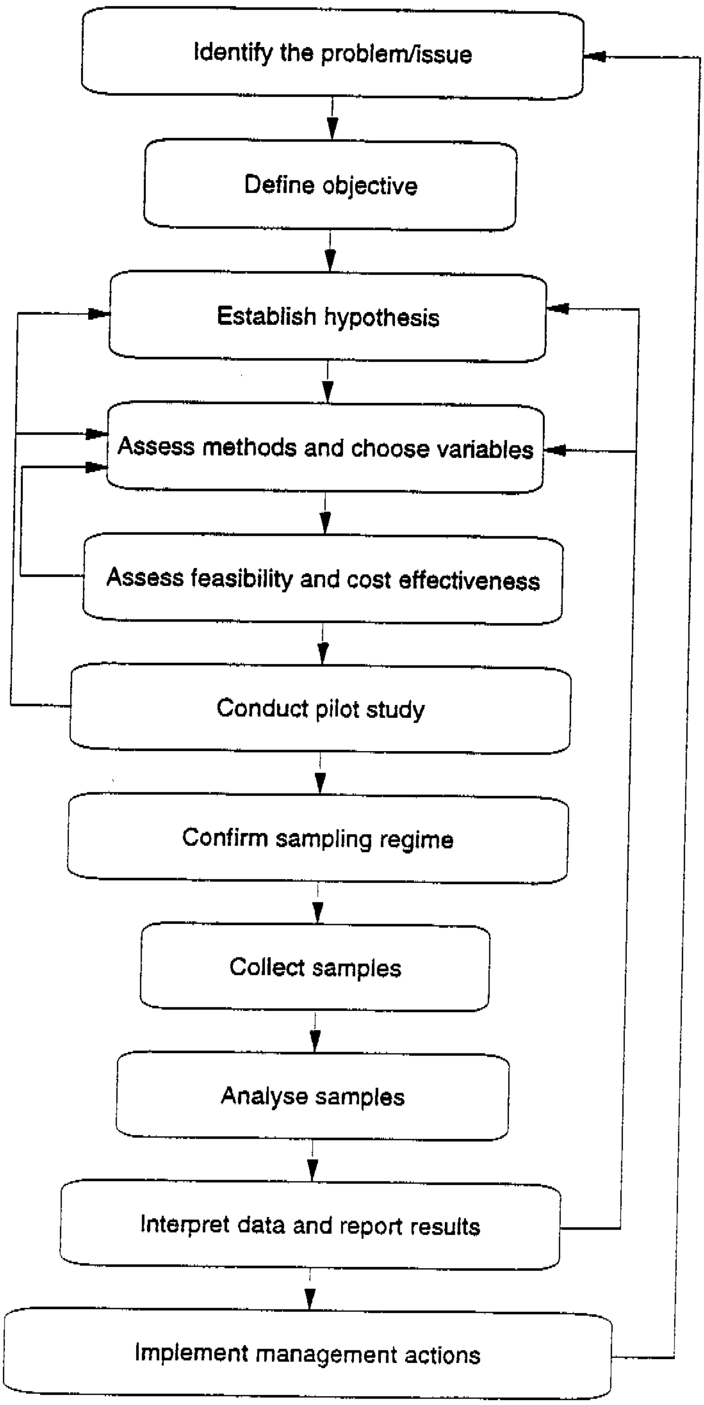
Table1 Summary of key points to consider when using a framework for designing a wetland monitoring program (from Finlayson 1996a,b).

Identify the problem or issue	State clearly and unambiguously State the known extent and most likely cause Identify the baseline or reference situation
Set the objective	Provides the basis for collecting the information Must be attainable and achievable within a reasonable time period
Establish an hypothesis	Supports the objective and can be tested
Choose the methods & variables	Specific for the problem and provides the information to test the hypothesis Able to detect the presence of and assess the significance of any change Identifies or clarifies the cause of the change
Assess the feasibility & cost effectiveness	Determine whether or not it can be done regularly and continually Assess factors that influence the sampling program: availability of trained staff; access to sampling sites; availability and reliability of specialist equipment; means of analysing and interpreting the data; usefulness of the data and information; means of reporting in a timely manner Determine if the costs of data acquisition and analysis are within the budget
Conduct a pilot study	Time to test and fine-tune the method and specialist equipment Assess the training needs for staff involved Confirm the means of analysing and interpreting the data
Collect the samples	Staff should be trained in all sampling methods All samples should be documented: date and location; names of staff; sampling methods; equipment used; means of storage or transport; all changes to the methods Samples should be processed within a timely period and all data documented: date and location; names of staff; processing methods; equipment used; and all changes to the protocols
Analyse the samples	Sample and data analysis should be done by rigorous and tested methods The analyses should be documented: date and location; names of analytical staff; methods used; equipment used; data storage methods
Interpret the data and report the results	Interpret and report all results in a timely and cost effective manner The report should be succinct and concise and indicate whether or not the hypothesis has been supported and contain recommendations for management action, including further monitoring
Evaluate the project	Review the effectiveness of all procedures and where necessary adjust or even terminate the program

Figure 1 A framework for designing a wetland monitoring program (from Finlayson 1996a,b).



Biological monitoring

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Abstract

The range of biological monitoring programs developed at ***eriss*** are described. The approach adopted encompasses a range of indicators to allow for early detection of short term impacts and detection of longer term impacts. Practical requirements for producing consistent, reproducible results in biological monitoring are also discussed, as are considerations for data management using the ***eriss*** macroinvertebrate relational database as an example.

Keywords: early detection, community structure, macroinvertebrates, relational database

1 Introduction

Biological monitoring involves the systematic collection of data or information about biological responses over time, in order to evaluate environmental changes and thus ascertain the extent of compliance with a predetermined standard or position (adapted from Finlayson 1996). At ***eriss*** biological monitoring techniques have been developed to detect possible impacts arising from mining activities in the Alligator Rivers Region. Monitoring to date has focused on aquatic systems after a review of literature determined that fully aquatic organisms (or life stage of organisms) were most at risk from the release of mine waste-waters to the environment (Humphrey & Dostine 1994). Biological monitoring using benthic macroinvertebrates commenced in the late 1980s in the South Alligator River in response to a proposal to mine gold and uranium at Coronation Hill. Though mining did not go ahead at Coronation Hill, research by ***eriss*** has nevertheless resulted in a valuable baseline data set. Conversely, a biological monitoring program has been developed for the Magela Creek system where uranium mining on the Ranger lease has taken place since the late 1970s (Humphrey et al 1990).

The implementation of biological monitoring programs requires a high degree of protocol development and documentation to ensure consistent reproducible results. Thought also needs to be given to how data derived from biological monitoring can best be stored to ensure effective use of resources and data integrity. A relational database has been developed at ***eriss*** to store and manage macroinvertebrate data collected from the region.

2 Biological monitoring at *eriss*

It has been recognised that no 'ideal' indicator organism exists. The selection of complementary indicators (ie those that integrate somewhat different aspects of environmental stress) is particularly useful. For example, measurements of populations, communities and ecosystems tend to be more appropriate compliance indicators for judging achievement of ecosystem objectives, while measurements performed on individuals will tend to be better diagnostic and early warning indicators (Cairns et al 1993). Using these principles, ***eriss*** has developed a comprehensive and sensitive biological monitoring program to provide 'early warning' of short-term (acute) effects of waste-water releases and detection of longer-term effects (delayed in expression or chronic) of mining generally (Humphrey & Dostine 1994, Humphrey et al 1990, 1995).

2.1 Early detection of short-term effects

An early detection type of biological monitoring was judged to be necessary to detect any unexpected, harmful responses occurring during releases of waste waters from the mine. Thus, if necessary, releases could be quickly adjusted or terminated, so reducing the risk of any adverse effects occurring in the stream itself (Humphrey & Dostine 1994). A creekside monitoring system has been developed to this end.

The creekside monitoring system uses organisms in containers located on the creek bank which are exposed to a flow of appropriately diluted waste water pumped from the creek. Tests so far have been developed for two species of freshwater snail (*Amerianna cumingii* and *A. carinata*) and two species of fish (*Mogurnda mogurnda* – Purple-spotted gudgeon; and *Melanotaenia nigrans* – Black-striped rainbow fish). Snails are monitored for changes in reproduction, early development and juvenile mortality, while fish are monitored for larval mortality and growth (Humphrey & Dostine 1994).

Organisms for use in the tests were selected according to the following criteria:

1. Sensitivity to mine waste waters comparable to those used in lab toxicity testing.
2. Low (natural) mortality when exposed to creek waters.
3. At least one organism to provide early feed-back of adverse effects in a readily identifiable way.
4. Responses should be varied (sub-lethal to acute).
5. Organisms from different phyla and/or trophic levels represented to cover the broadest possible range of potential impacts on biota.
6. Easy to culture.
7. Biology should be understood so results can be interpreted.

2.2 Detection of longer term effects

Biological monitoring by ***eriss*** to detect longer term effects of mining on the aquatic environment have been of two main types: 1) investigation of natural communities and populations; and 2) chemical monitoring of biota (bioaccumulation).

2.2.1 Natural communities and populations

Community based approaches to monitoring are robust because they incorporate a variety of species responses, however community responses to environmental stressors are complex and, in most cases, not well understood. This means that community level monitoring programs have a good chance of detecting changes in the environment but the precise mechanisms responsible for that change may not be understood. Studies at ***eriss*** have focused on 1) benthic macroinvertebrate communities and populations; 2) daily counts of fish migrating upstream past the mine; and 3) fish communities in billabongs. Observations of communities are made at the end of the Wet season to detect any effects of waste-water releases during that time and to assess the success of Wet season breeding. Detection of impact relies on statistical comparisons of post-release data with historical baselines.

Benthic macroinvertebrate communities are sampled at the end of the Wet season from two lotic habitats (macrophyte in flowing water and sand beds) at sites upstream and downstream of the mine and in nearby catchments with similar types of streams ('controls'). The design is based on the BACIP approach (Faith et al 1995; Humphrey et al 1995). Fish migration aims to quantify the number of fish moving from spawning and feeding habitats on the floodplain to Dry season refuges upstream of the mine. This migration is an essential survival strategy and released waste waters should not impair recruitment and subsequent movement of fish. Fish communities are monitored in billabongs of Magela Creek at the same time of year as macroinvertebrate sampling. Billabongs can represent Dry season refuges (Bishop et al 1995) and depositional zones in the creek system(Wasson 1992). Billabongs may thus be of ecological significance due to long-term accumulation of contaminants and future invertebrate monitoring may be extended to these habitats.

2.2.2 Bioaccumulation studies

Bioaccumulation studies focus on organisms that accumulate substances in their tissues in a way that reflects environmental levels of those substances or the extent to which the organism has been exposed to them. They may also be used to detect what may otherwise be very low, undetectable environmental levels of substances (Hellawell 1986). At ***eriss***, baseline concentrations of chemical elements in body organs of fish (Martin et al 1995) and soft parts of freshwater mussels (Allison & Simpson 1989) have been determined so that future concentrations might be compared. These taxa were chosen because they are long-lived and, in the case of fish, at the top of the aquatic food-chain.

3 Implementation of biological monitoring programs

Well-designed studies do not necessarily yield data that can be used in addressing project objectives. The additive effects of failure to implement laboratory protocols, equipment malfunction unnoticed by inexperienced staff, poorly designed data sheets that promote transcription errors, inappropriate analysis etc may result in poor quality data (Norris & Georges 1993). In monitoring programs the need for consistent and reproducible techniques and results is of the utmost importance given that data is collected repeatedly over time, often with the aim of detecting temporal trends. Undocumented changes in methods will confound any real temporal changes that may have taken place.

Some of the requirements for ensuring consistency and reproducibility are:

1. Clear documentation of all aspects of the sampling design and regime eg the locality of sampling sites (including map references, GPS references and descriptions of access routes), all field and laboratory procedures, and standardised field and data sheets.
2. Training of field staff in sampling protocols and sampling theory to ensure consistency in collection techniques ie results should be independent of who does the collection.
3. Documentation of required quality assurance procedures.

4 Data management and the *eriss* relational database for macroinvertebrate data

The planning phase of biological monitoring programs should include consideration of how data arising from the program will be stored and managed. This section does not aim to cover data management theory in detail but to point out practical considerations relevant to biological monitoring programs. A database is an organised collection of information or data (eg an address book is a database as it organises people into specific categories: names, phone numbers and addresses). Databases should not be confused with other types of files that contain data. Spreadsheets, for example, are designed for data manipulation not for data storage. Some of the properties that distinguish databases from other forms of data files are (from Beynon-Davies 1989):

1. Data integration – implies that a database should be a collection of data which has no redundancy, that is, no unnecessarily duplicated or unused data.
2. Data integrity – implies that when maintaining data we can be sure that no inconsistencies are likely to arise in the database eg if the name of a macroinvertebrate taxon were to change, all previous records including the original name would need to be changed.
3. Separate logical and physical views of data. The major idea behind the database concept is the attempt to model the natural or logical structure of data and separate this from the exigencies of any particular implementation of the data.

Databases can have in-built integrity rules to ensure the accuracy and correctness of data (eg in the COUNTS table of the ***eriss*** macroinvertebrate database only invertebrate codes listed in the look-up table FULLCODES will be accepted during data entry). Despite these in-built checks it is inevitable that most data sets will contain some errors. Even gross errors may go undetected, profoundly affecting the outcome of analysis (Norris & Georges 1993). Data validation is one practice that can reduce the level of error in databases. Validation consists of checking for transcription errors when data from field and laboratory data sheets is entered on to the database. Data verification and procedures designed to minimise errors can also be performed at each step in the implementation of a monitoring program. Verification can range from calibration of field equipment to verification of data after it has been entered onto a database. Data verification can take a number of forms including scanning for outliers, and checking for known ranges, if appropriate (Norris & Georges 1993).

Relational databases are one type of database that organise data into a series of linked tables (or files). A relational database can be a useful tool in biological monitoring programs as it can store the range of information relevant to the program in an efficient way. For example, the ***eriss*** macroinvertebrate database contains information ranging from the location of sampling sites through to the date on which sample specimens were identified and by whom (*dbase Figures 1,2,3*). In relational databases all data is organised into 2-dimensional tables which are constrained in the following ways:

- All entries in a column (or field) must be of the same kind eg for invertebrate counts you would only have whole counts, not fractions or presence/absence records.
- All columns must be assigned distinct names eg 'Date' would be an inappropriate field name in a table as it could refer to the date a sample was collected, the date it was processed, the date specimens were identified or the date the data was entered into the table.
- The ordering of columns is not significant ie the value of one column is not a function of a preceding one.
- Each row must be distinct ie duplicate rows are not allowed in any one table. This means that each table must have a so-called primary key (an attribute or combination of attributes whose value(s) uniquely identify the rows). These primary keys are also used to link the tables together.

- Each column/row intersection (cell) in a relation should contain a single value.

Relational systems are designed to operate on whole files (tables) rather than columns or rows. Tables are structured so that every item can have a value assigned eg in the SAMPLES table of the ***eriss*** database every sample (represented by sample number) has information about the site and habitat of collection, the collection date, replicate number etc. This structure provides the most efficient structure for data storage. When reporting is required, copies of the relevant data can be copied into the appropriate software packages (such as statistical and graphical packages).

6 Conclusion

Biological monitoring is an essential part of ensuring highly valued aquatic ecosystems such as those found in the Alligator Rivers Region are not altered through activities such as mining. The use of a range of indicators gives the greatest guarantee that any potential impacts are detected. The implementation of biological monitoring programs requires a high degree of detailed documentation of protocols to ensure consistency and reproducibility of results. Results and associated information can be stored effectively in relational databases.

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1

Site : MAGELA CK SITE 1 | Method : 1HR LIVE PICK

Habitat : MACRORIFFLE | Collection Date : 3/05/95 | Replicate : 1.00

Field Mesh Size : 500.00

# Vials	Mesh Size (um)	% Subsampled	ID Date	Operator
1	500.00	100.00	10/04/96	Carel
2	500.00	100.00	28/03/96	Rutho

Species Code	Count
ATYIUUUX	1
BAETZZZN	2
BEROS01L	1
CERAS02L	3
DYTIS13A	1
HELLFORL	9
HPTIUUUL	11
HYPHZZZX	2
LESBZZZX	11

Site :

Method :

Habitat :

Collection Date :

Replicate :

Field Mesh Size :

# Vials	Mesh Size (um)	% Subsampled	ID Date	Operator
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Species Code	Count
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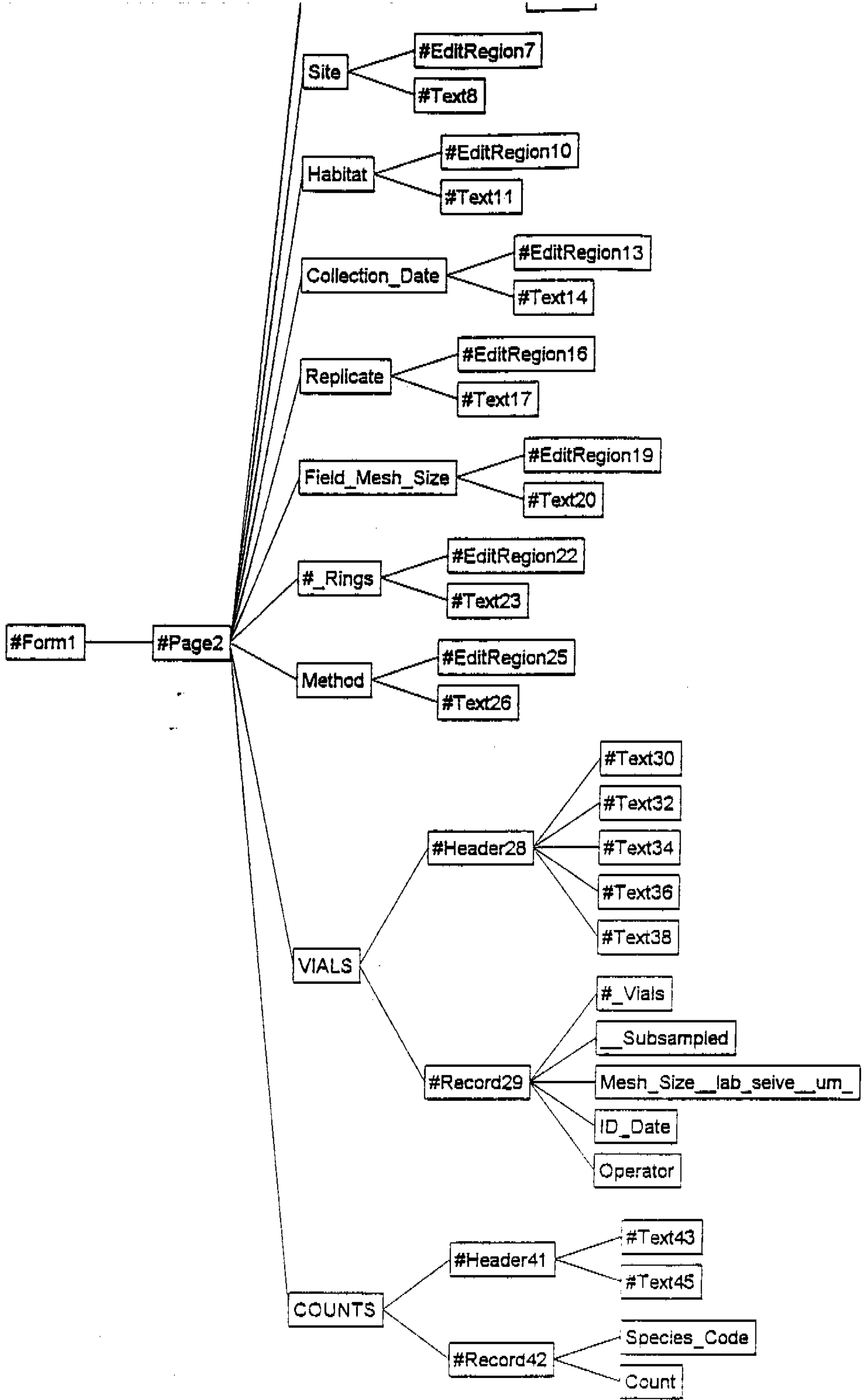

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Ecotoxicology in the Wet-Dry tropics

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Abstract

Ecotoxicology is a relatively new field, and is still evolving. It seeks to understand how toxic chemicals affect the environment and ecosystems. Representative organisms are used in toxicity testing to investigate the fate of pollution, especially where there may be chemical contamination. It is crucial that toxicity of chemicals or substances be prioritised and the relevance of effects be addressed. In order to protect diversity, certain decisions are made regarding toxicity testing protocols. To date, single species tests are widely used, but are not without criticism. Single species tests have been developed at ***eriss*** for whole effluent testing of the waste waters from a uranium mine in the Wet-Dry tropics. The protocols have been handed over to the regulatory bodies, and these protocols have since been utilised in a range of environmental protection and risk assessment issues in the Wet-Dry tropics.

Keywords: ecotoxicology, pollution, toxicity test, indicator species, Wet-Dry tropics

1 Introduction

Ecotoxicology seeks to understand how toxic chemicals affect the structure and function of natural ecological systems (populations, species assemblages, communities and ecosystems) (D. Baird pers comm).

Representative organisms have been used extensively in toxicity testing to investigate the fate and effect of pollutants in natural systems. Pollution itself arises from many diverse human activities, and has the potential to cause effects directly in the area of use, or can disperse widely around the world eg organochlorins, being highly volatile, disperse widely from the point of use (Forbes & Forbes 1994).

2 Chemical contamination

There is increasing pressure to find better ways of protecting crops from insects or disease, and hence better yields of production, and generally it is chemical compounds such as pesticides and herbicides that are used. Developing countries especially utilise large amounts of pesticides, and hence areas of high biodiversity, eg Brazilian rainforests, are under increasing threat.

2.1 Global fractionation of pollutants

There is nowhere on the planet that is not subject to pollutants, due to global fractionation. The fate of compounds can be highly variable, as they can be transported over vast distances depending on their chemical properties. Consideration must be given to the problems chemicals such as chlorinated compounds will cause globally, ie CFC's do not become deposited; instead they are found in polar regions and in the ozone layer.

2.2 Problems of chemical analysis

Many substances or chemical compounds that are in use today are extremely toxic. There has been a trend towards using smaller amounts of certain chemicals but at higher concentrations. It is also possible that toxic effects may be present in a natural system, but in quantities too low to be analysed by current methods. If the trend of using more complex toxic compounds persists, it is possible that they will be more difficult to identify, and subsequently analyse, in a particular environment.

2.3 Problems of ignorance

If detection of a toxicant is difficult/expensive etc there is a tendency to ignore it. Toxicity testing is expensive, and is usually a regulatory requirement eg ERA Ranger Mine whole effluent testing of mine waste waters.

2.4 Problems of priority

Identifiable catastrophic events eg oil spills, more often receive wide media attention. However, there are the low-level 'silent' compounds which may go unnoticed, but are as pervasive as events on a much larger scale. How we prioritise toxicity of compounds or chemicals is often based on the publicity they receive.

2.5 Problems of relevance

Addressing what effects are relevant is crucial in determining and prioritising importance of a toxicant or possible effect. Ecologically relevant endpoints need to be determined that are also relevant at population/community levels, to ensure protection of a natural system.

3 Protecting biodiversity

Biodiversity is the number, variety, and variability of living organisms. It is not possible to test every single species from an ecosystem and determine which species would be adversely affected more than others from a particular toxicant. Instead, representative organisms are selected based on several criteria.

Environmental quality standards are designed to protect 95% of the organisms, based on a minimal number of selected species. The underlying assumption is that the selected species are representative of a random sample from within the system. The questions which should be addressed are 1) whether 5% is too much to lose eg if the ecosystem is highly valued for certain species and habitat; and 2) is what is measured in a laboratory a true random sample of the distribution.

One ideal approach that can be taken is the following:

1. Design tests for making predictions about a particular kind of community or habitat eg tropical wetland, and try to incorporate field studies
2. Try to select 'indicator' or key species from the community which may be threatened
3. Address the effects upon the end points of such factors as seasonal or behavioural variations
4. Address the ecological consequences of pollutant-induced mortalities.

To enable such an approach a large database would be required of the ecosystem in question, and more often than not in the tropics, that level of information is not available.

4 Single species laboratory tests

As mentioned previously, economic, societal and political pressures will ultimately determine what is achievable in protecting an ecosystem. To date, single species tests are used due to several reasons, and certainly are not without criticism. More importantly, we need to look at the single species test and address options of improvement.

For example, water flea tests have a vast database available on how they respond to a wide range of different toxicants. Water fleas also reproduce asexually (parthenogenetic females) and therefore the genotype can be manipulated. They are relatively easy to maintain in laboratory cultures, have an optimum body size for experiments (ie they are large enough to measure various responses), yet are still small enough such that sufficient numbers for replication can be obtained for testing. Water fleas also have a non-selective method of feeding, and are representative of the trophic level of herbivores/grazers. Being non-selective feeders, they are unable to avoid exposure to contaminated food.

Standard tests using water fleas are used in OECD Guidelines, and it is from these guidelines that site specific tests may be modified or derived eg the test used by ***eriss***.

5 Protection of wetlands in the Wet-Dry tropics

The toxicity testing protocols at ***eriss*** were developed to ensure adequate protection of the waterways of the Alligator Rivers Region from the activities of mining, particularly the management of mine waste waters (Hyne et al 1996). Initially, a broad survey was conducted to collect and identify potentially suitable species from the local creeks and billabongs, and being located within a national park, certain restrictions prevent the importation of exotic species into the area. The criteria used were based on the above mentioned points, and from a starting list of approximately 20 species, three species were eventually selected as suitable. The species chosen were *Moinodaphnia macleayi* (water flea), *Hydra viridissima* (green hydra), and *Mogurnda mogurnda* (purple-spotted gudgeon). Endpoints for determining an effect are based on reproduction, population growth and sac fry survival respectively.

Whole effluent tests using the three species concurrently were carried out using mine retention pond waters and natural receiving waters from Magela Creek. Test treatments or concentrations were established by preparing serial dilutions of the toxicant and receiving waters, from 0 to 32%. The most sensitive response of the NOEC (No-observed-effect-concentration) and LOEC (Lowest-observed-effect-concentration) from the three species was taken, and a nominal safety factor applied. Results were then used in conjunction with pure chemical analyses, and a dilution rate established for the release of mine waste water that would ensure no adverse effects on aquatic life downstream of the release.

These protocols have been successfully applied to several areas other than mining eg effects of herbicides on non-target aquatic organisms, tourism impacts on a plunge pool, ANZECC Water Quality Guidelines for U and CU.

6 Types of toxicity tests

In addressing the potential threats to wetlands it is necessary to ascertain the mode of transport and the fate of the toxicant eg application of herbicide in pellet form is potentially more toxic to sediments. The type of test and test conditions should reflect the nature of the toxicant, and target as well as non-target organisms. For effects in the aquatic environment, there are several tests available including the cladoceran reproduction, hydra population growth, sac fry survival, algal and lemna growth. Sediments can be assessed for toxicity using chironomids or cladocera. Actual running of the tests can be done by static renewal of test solutions every 24 or 48 hours, or by using flow-through systems, depending on available resources. The decision to use site specific tests and local species versus existing standard tests also needs consideration.

Acute or chronic toxicity tests can be utilised for different purposes. Acute tests assess part of the life cycle of an organism and generally provide a less sensitive endpoint eg EC50, as compared with chronic tests which expose a significant part of the lifecycle of the organism to the toxicant eg water flea reproduction test using NOEC and LOEC responses.

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