supervising scientist report **157**

Assessment and monitoring of coastal change in the Alligator Rivers Region, northern Australia

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Environment Australia
Department of the Environment and Heritage

supervising scientist

We acknowledge the financial support provided by the Portfolio Marine Group of Environment Australia to initiate this work and to provide the impetus to develop a broad stakeholder group and advisory committee. The many people from agencies and organisations in the Northern Territory and elsewhere who provided advice and access to data and information are warmly thanked. The combined inputs have enabled us to collate and assess a vast amount of information as a basis for determining monitoring and management options for the coastal lands that surround van Diemen Gulf and those elsewhere in tropical Australia.

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This report should be cited as follows:

Eliot I, Saynor M, Eliot M & Finlayson CM 2000. *Assessment and monitoring of coastal change in the Alligator Rivers Region, northern Australia*. Supervising Scientist Report 157, Supervising Scientist, Darwin.

The Supervising Scientist is part of Environment Australia, the environmental program of the Commonwealth Department of Environment and Heritage.

Supervising Scientist
Environment Australia
GPO Box 461, Darwin NT 0801 Australia

ISSN 1325-1554

ISBN 0 642 24361 1

Printed in Darwin by NTUniprint.

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Chapter 1 Introduction to the coastal monitoring program

1.1 Introduction

The Environmental Research Institute of the Supervising Scientist (***eriss***) at Jabiru initiated a program to assess and monitor coastal change in the Alligator Rivers Region of the Northern Territory. It commenced in October 1996 with funding support for 12 months from the Portfolio Marine Group of Environment Australia. The Environmental Research Institute of the Supervising Scientist extended support for the program until February 1998. The program is currently maintained as part of the core wetland research activities of the Institute.

This report presents an overview of progress in the monitoring program from October 1996 to February 1998. Papers presented in the report detail initiation of the monitoring program and establishment of the framework supporting information acquisition and management. They outline progress with projects commenced under the program, audit existing information and describe areas requiring further investigation.

1.2 Area of interest

Development of a regional capacity to measure and assess environmental change will provide a contribution to the National Strategy for Ecologically Sustainable Development agreed by the Council of Australian Governments in 1992. The capacity to measure and assess variation in biophysical processes and land uses has been recognised as a significant component of this strategy. Further, such information can contribute to State of the Environment (State of the Environment Advisory Council 1996) and Marine Environment Report (Zann 1995).

The Alligator Rivers Region in the wet-dry tropics of northern Australia was selected by Environment Australia and collaborating agencies as a key study area for the monitoring of natural and human-induced coastal change. The Region contains the floodplain wetlands of Kakadu National Park, of internationally acclaimed natural and cultural heritage value, several major rivers, and large areas of coastal plain draining into van Diemen Gulf. Its wetlands are already undergoing significant ecological change and, by nature of their elevation and hydrology, are particularly vulnerable to the impacts of climate and other changes, both natural and human-induced (Bayliss et al 1997, Eliot et al 1999, Finlayson et al 1997).

Areas of specific interest in the Alligator Rivers Region include the lowland reaches of inundated floodplains, low-lying seasonally inundated floodplains, deltaic estuarine floodplains and coastal plains described by East (1996). Together, these four geomorphologic units broadly define the coastal zone of the Region. It is a zone of marked interaction between fluvial and marine processes. Tides and other fluctuations in sea level, such as storm surge and those associated with short-term variation in climate, interact with fluvial processes. They give rise to the complex patterns of tidal creeks and salt flats that characterise much of the coastal zone.

1.2.1 The coastal zone

The major part of the Alligator Rivers Region, of which Kakadu forms a significant part, 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 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 (Finlayson & von Oertzen 1996a).

The broad coastal plains of the Alligator Rivers Region lie in a narrow band of elevation, 3–4 metres above Australian Height Datum. On the South Alligator River they fall approximately 50 cm in over 70 km. As a result, small fluctuations in river discharge and sea level associated with variation in climate are likely to have far reaching effects on riverine processes, particularly on the tidal hydrology of the streams and the distribution of vegetation on the floodplains. This has been demonstrated through detailed research into the evolution of the floodplains and through systematic accounts of major ecological changes that are currently taking place in the wetlands of the Region (Woodroffe et al 1986, Finlayson & Woodroffe 1996, Bayliss et al 1997, Finlayson et al 1997). The extreme sensitivity of the Region to fluctuations in climate and sea level, such as seasonal variation in weather and those related to El Nino – Southern Oscillation (ENSO) events increases the viability and significance of the monitoring program.

The floodplain wetlands of Kakadu National Park have a high conservation value and cannot be managed in isolation from the remainder of the Alligator Rivers Region or, indeed, lands bordering on van Diemen Gulf (Finlayson et al 1998b). The wetlands are already undergoing major ecological changes and can be expected to change even further, especially given predicted climate change and rise in sea level (Finlayson & Woodroffe 1996, Bayliss et al 1997, Finlayson et al 1997). The ecological character of the Region is partly described, but information upon which changes in character of the valued wetland habitats can be identified are cursory.

1.2.2 Proposed research

Research proposed in the monitoring program includes several large-scale studies monitoring atmospheric and hydrodynamic processes in van Diemen Gulf and the rivers, as well as mapping and monitoring projects specific to environmental change in the wetlands of the Region (Eliot et al 1999). In conjunction with the field-monitoring program, information management will be addressed, and a Geographic Information System structure established for effective data collation, analysis and management across the Region. Participation of other agencies in the program is central to improving data and information management, and will bring wide-ranging expertise to this multidisciplinary initiative.

Monitoring will address processes that influence the stability and rate of change of the floodplain environments (eg Finlayson et al 1997), in particular the switching between saline and freshwater systems with seasonal change from wet to dry conditions (Eliot et al 1999). In addition to studies of large-scale forcing conditions, a suite of local processes will be examined. These include:

- destabilisation of levees vegetated by mangroves;
- headward expansion of tidal creeks;
- basin salinisation; and
- sediment accumulation on the coastal plains.

Existing data sources will be identified and recorded. Data management protocols will be examined and lead to the development of standardised procedures for establishing a metadatabase and a spatial bibliography (Finlayson 1997).

This strategy will enhance previous and current work on coastal monitoring by Commonwealth and other agencies throughout Australia. It will assist in translating international agreements and governmental policy into management action at a local level. Detailed knowledge of biophysical processes in wetlands and the coastal environment are lacking. This lack hinders effective planning and management in these areas (Storrs & Finlayson 1997, Finlayson et al 1998a,b). As coastal wetlands are vital to Australia's natural, cultural, social and economic systems and there is increasing awareness of the need for their ecologically sustainable development (Williams 1998), this proposal is timely.

1.3 Background to the monitoring program

1.3.1 Philosophical framework

Change in physical, cultural, social and economic systems is continuous. Therefore, a key factor to be considered is whether environmental change or the rate of change can be perceived as having adverse effects on natural and human systems. On one hand, a heightened perception of change can lead to increased activity to identify, record and implement measures to deal with the changes. On the other hand, a diminished perception of change can result in relaxing measures used in the past to address the negative effects of change. These perceptions have implications that manifest in effects on the natural, cultural, social and economic systems and responses by governments to them.

Governmental responses to such environmental change have been translated into action at a state, territory and local government level through the Australian Intergovernmental Agreement on the Environment (Commonwealth of Australia 1992). More specifically, coastal and marine management problems have been identified by DEST (1995), the Australian Resource Assessment Commission (1993) and Zann (1995). To a varied extent, the implications of environmental change are recognised by all spheres of government through environmental management policies, such as the Commonwealth Coastal Policy (DEST 1995). However, translation of the policies into management action is not always complete, with commitment to the acquisition of a detailed knowledge of biophysical processes and responses to them, as a basis for planning and management at a local level, still required.

Maintenance of the coastal monitoring program at the Environmental Research Institute of the Supervising Scientist will enable identification of potential changes pertinent to the Alligator Rivers Region and the wet-dry tropics in general, and refinement of methods used to assess the vulnerability of coastal areas to such change. Summary scenarios will then be developed and the potential dimensions, significance and implications of changes will be highlighted to assist land managers in Kakadu National Park and the wider Region to formulate appropriate management strategies.

1.3.2 Current use and values of the Alligator Rivers Region

Major uses and values of the Region are conservation, tourism and recreation, use by Aboriginal people, uranium mining and research activity (Finlayson & von Oertzen 1986b, Bayliss et al 1997). The coastal wetlands constitute the greater part of the coastal zone. 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 (Finlayson et al 1997, 1998a).

Kakadu National Park is the most important natural, cultural, recreational and tourist resource in the Alligator Rivers Region. The importance of its natural and cultural heritage values are recognised internationally, and it is listed as a UNESCO World Heritage Area. The Aboriginal people of the area, the Bininj, largely own the Park. It is leased by the Commonwealth of Australia and managed by Parks Australia North, an agency of Environment Australia (Kakadu Board of Management and Parks Australia 1998).

Uranium is mined within the catchment of Magela Creek, a tributary of the East Alligator River. The mining leases and nearby townsite of Jabiru have been excised from the Park (Finlayson & von Oertzen 1986b). 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. This has been pursued through comprehensive environmental research and monitoring programs at the Ranger uranium mine site at Jabiru East and on the floodplains of Magela Creek (Johnston 1991, Finlayson 1993, Humphrey & Dostine 1994, Humphrey et al 1990, 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 Region and minimisation of these effects after decommissioning and rehabilitation. The coastal component of the research has focussed on downstream effects of mining, however, much of the information 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. This information base has underpinned the development of a wetland research program with a strong emphasis on monitoring change and involving local community groups (Spiers & Finlayson 1998).

1.3.3 Current research and prior activities in the Region

Extensive scientific research has been undertaken in the Alligator Rivers Region. It commenced in the early 1970s with the Alligator Rivers Region Environmental Fact Finding Study (ARREFFS) which, at the time, was the most comprehensive study of its type ever undertaken in Australia (Christian & Aldrick 1977). Results of the ARREFFS and the subsequent Ranger Uranium Environmental Inquiry were used in the environmental assessment of the impact of mining and milling uranium ore (Ranger Uranium Mines Pty Ltd 1974a,b & 1975) in the Region (Fox et al 1977). Research has continued with an emphasis on the management of Kakadu 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, which carry a much larger population.

Literature sources, including published scientific papers, reports and unpublished reports were collated by Bayliss et al (1997) as part of an assessment of the vulnerability of the Alligator Rivers Region to the possible effects of predicted climate change and rise in sea level. The literature was used to:

- Identify climatic and other changes that are pertinent to the assessment of the vulnerability of coastal and wetland areas of the Alligator Rivers Region (ARR) and to Kakadu National Park (KNP).
- Review the methods and approaches used to assess the vulnerability of coastal areas to natural and human induced change.

- Develop summary scenarios for climate and other changes that can be related to the Alligator Rivers Region and Kakadu National Park in general, and to the Magela floodplain in particular.
- Provide background descriptive information on the areas that could be affected by change by way of natural, cultural, social and economic resources of the areas.
- Review the specific and cumulative effects of the change processes identified in the areas.
- Assist in the development of an assessment framework and highlight the dimensions, possible significance and the potential implications of the changes.
- Gain an understanding of types of responses to change that would be relevant to the Alligator Rivers Region and Kakadu National Park.
- Provide a benchmark for determining the actions most suited to implementation across the Alligator Rivers Region and Kakadu National Park.

Additional sources of information relating to the Alligator Rivers Region that are considered relevant to this strategy include:

- Alligator Rivers Region Geographic Information System (ARRGIS) (Riley 1992, Devonport & Riley 1993);
- Environmental Resource Mapping System (ERMS) for Kakadu National Park (Ryan et al 1995);
- Satellite imagery for the Alligator Rivers Region and Kakadu National Park highlighting specific environmental characteristics (Hausknecht & Milne 1998, Milne et al 2000) (see Paper 2);
- Aerial photography for the Region, Kakadu National Park and specific localities such as the mine lease areas, Point Farewell and areas of salt water intrusion (Cobb et al 2000, Paper 8 in this volume);
- Thematic maps of the natural resources of the area (eg Schodde et al 1987);
- Meteorological, hydrological and tidal prediction data (see Papers 3, 4 & 5);
- Quantitative results of the monitoring programs (Finlayson 1988, Johnston 1991, Humphrey & Dostine 1994, Humphrey et al 1990, 1995, Bishop et al 1995); and
- Oral and written history of land use and environmental change (see Paper 6).

Although a range of information is available, there has been considerable information loss — including missing copies of scarce reports, data from field investigations and memoranda outlining results of research. As a result, information management is a significant issue.

1.3.4 Selection of the Alligator Rivers Region as a monitoring area

Critical issues confronting the coastal zone have been identified many times. The Commonwealth Government has recognised them in numerous inquiries and discussion papers. The most recent of these are the report of the House of Representatives Standing Committee on Environment Recreation and the Arts (1991), the final report of the Resource Assessment Commission Coastal Zone Inquiry (Australian Resource Assessment Commission Coastal 1993) and the Commonwealth Coastal Policy prepared by the Department of Environment, Sport and Territories (1995). The last of these also provides the policy context for this proposal.

The Commonwealth has responsibilities that significantly affect management of the coastal zone. It is necessary to ensure that these responsibilities are carried out effectively. The Commonwealth Coastal Policy is the basis for *putting the Commonwealth's house in order*. Thus, the Commonwealth Coastal Policy provides a framework within which the activities of Federal Government departments and agencies that may have an impact on the coastal zone will be developed and implemented. Management of the coastal wetlands of Kakadu National Park is a Commonwealth activity that falls within the ambit of the Commonwealth Coastal Policy.

Selection of the Alligator Rivers Region for the monitoring and management of coastal change arose from recognition of the significance of Kakadu National Park. It is a major regional resource in the wet-dry tropics. Other contributory factors include the apparent susceptibility of the Region to change, management of the Park by Aboriginal people and the Commonwealth Government for the purposes of conservation and tourism, and the scope offered to integrate a range of coastal initiatives being implemented within a single Commonwealth Government portfolio.

1.3.5 Relevance to the wider wet-dry tropics

Despite its susceptibility to change, the Alligator Rivers Region is relatively untouched in comparison with other areas. Therefore its management can serve as a benchmark for management of other parts of the wet-dry tropics.

Information and experience gained from the survey and assessment process developed in the Alligator Rivers Region should assist other government agencies and Aboriginal organisations to appreciate and manage problems underlying environmental variability in remote areas. For example, outcomes of the assessment will have ramification for the Kimberley coast, Arnhem Land and parts of the Northern Territory and Queensland bordering on the Gulf of Carpentaria, given the biogeographic similarities and the absence of an equivalent information resource and research infrastructure in these areas (Finlayson 1995, Finlayson et al 1998b).

Wetlands in the wet-dry tropics encompass seasonally inundated floodplains and swamps, coastal salt flats, mangrove swamps and estuaries. The conservation value of these wetlands is well recognised, as are the physical and biological linkages between them (Storrs & Finlayson 1997). However, the information base is uneven and, in many instances, poor. A broad scale inventory base for these valuable ecosystems does not exist.

1.4 Objectives of the monitoring program

The objectives of the coastal monitoring program are to:

- Coordinate and document change in the Alligator Rivers Region, including Kakadu National Park and van Diemen Gulf, incorporating the coastal wetlands, shores and nearshore waters.
- Provide information and advice to assist strategic planning, preparation of coast and catchment plans, and implementation of specific management programs.
- Enhance information management, including ownership of spatial environmental information.
- Establish a baseline and reference station to provide input to the National Coastal Monitoring Program under the Commonwealth Coastal Policy.

- Support the administration and operation of long-term monitoring programs that focus specifically on climate change implications for the management of the tailings dam and mine tailings and overburden stockpiles in the catchment of the Magela Creek.
- Audit the effectiveness of planning and management activities in Kakadu National Park and van Diemen Gulf.

1.5 Anticipated outcomes of the program

The coastal monitoring program will enable the principal scientific organisation of the Region, the Environmental Research Institute of the Supervising Scientist, to provide primary baseline information, particularly time series describing environmental change, for management of the floodplains and coastal zone of Kakadu National Park. In turn, the information will enable the Commonwealth managing authority, Parks Australia North, and the Traditional Owners to anticipate and respond to change in a manner that does not compromise the environmental and cultural values of the Region.

Anticipated outcomes include:

- Establishment of a coastal monitoring program, responsible for acquisition, analyses and dissemination of time series information describing biophysical change on the floodplains and coast of the wet-dry tropics.
- Development of a predictive capability for identifying potential environmental responses to climate change and sea level fluctuation.
- Establishment of long-term monitoring of key biophysical parameters in the wetlands and adjacent seas as a basis for assessment of environmental change and establishment of appropriate natural resource management strategies.
- Increased community awareness of the nature and scope of temporal variation in the floodplain environments of the wet-dry tropics.

1.6 Organisation of the report

The report opens with statements of intent and a description of the area of interest. This is followed by consideration of data collection and information management tasks that provide a framework for the monitoring activities. We then list details of projects contributing to an understanding of large-scale, regional processes and forcing conditions that underlay much of the environmental change occurring on the coastal plains, and identifying change at a local-scale. Finally we then discuss potential applications and accountability for work completed. The structure and organisation of the report is shown as a flow diagram in figure 1.1.

The report provides a hierarchical approach to the coastal monitoring program in two respects. First, the sequence of papers follows the order in which the monitoring program is evolving. Second, the completeness of papers presented varies with the hierarchical order. The most complete aspects of the monitoring program relate to its organisation. Even after two years collation, baseline information in many areas is incomplete and ongoing, and several planned projects remain to be implemented.

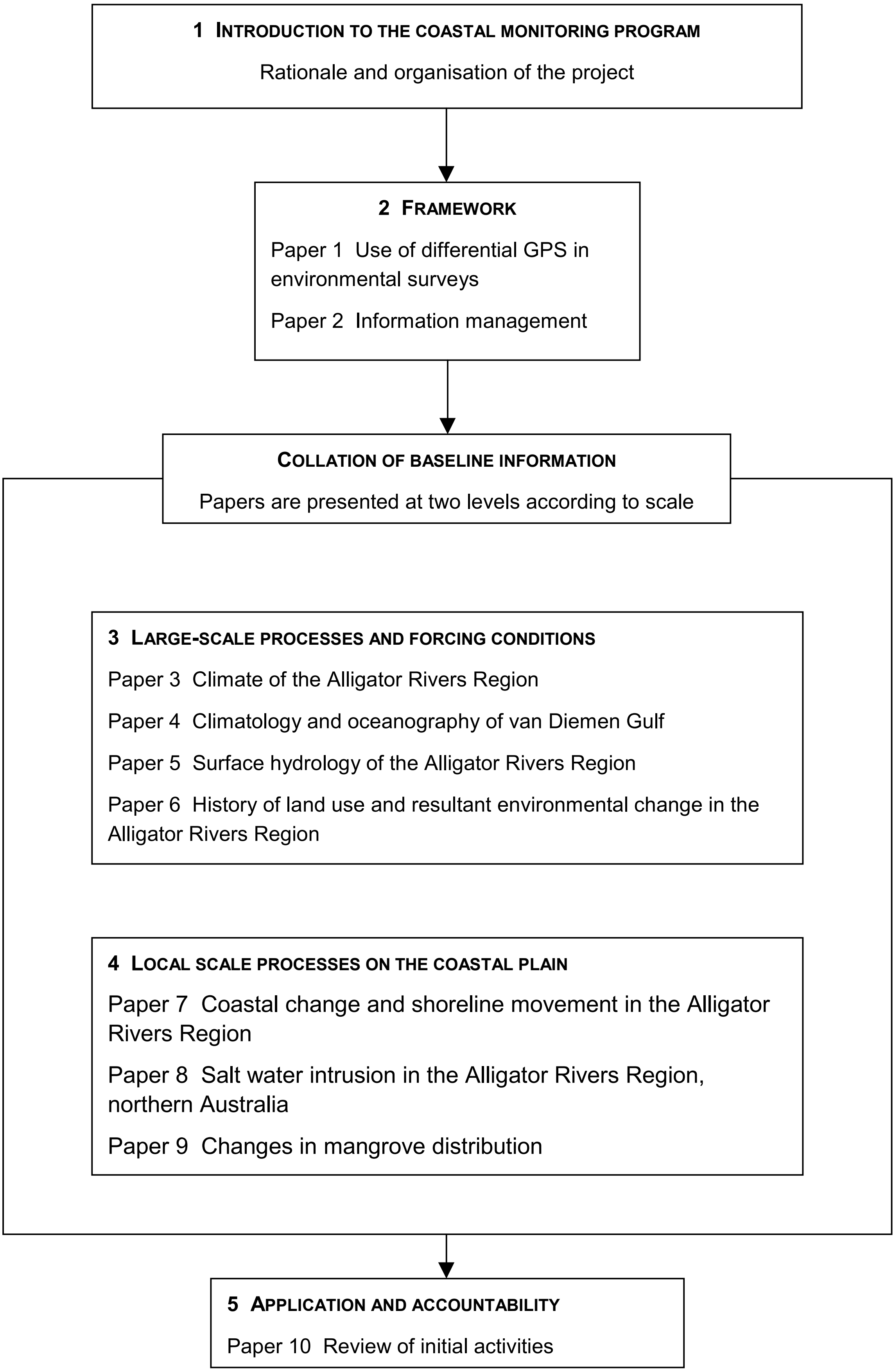

Figure 1.1 Organisation of papers in the report

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Chapter 2 Data collection and information management

2.1 Strategic approach

Sound management of coastal areas requires that people with an interest in the coast have access to a diverse range of information encompassing cultural, social, economic, ecological, biophysical and geophysical attributes of the environment. Managers in the Alligator Rivers Region have recognised the need for these types of information and a range of research projects have been undertaken to provide material for Park management and monitoring of the effects of uranium mining. Some of this material has direct application to addressing management issues specific to the coast of the Region. As a result, establishment of a coastal monitoring program in the Alligator Rivers Region developed in recognition of the needs of a diverse range of users to access environmental information of common relevance (Bayliss et al 1997, Eliot et al 1999).

The monitoring strategy is a multi-faceted approach to acquisition of information within the context of a careful assessment of information needs. Thus information management, including that of previously obtained information, is an important component of the program. Information should be gathered systematically, in consistent temporal and spatial contexts. This is necessary if reliable comparisons are to be drawn between suites of different data, such as the distribution of soil moisture and exotic weeds, or recurrent sets of similar information, for example change over time in the distribution of mangroves in a stream network. It requires adoption of formal procedures for acquisition of data that is accurately georeferenced. Further, development of sound information management techniques are required for archiving, retrieval and analysis of data. Together, they provide a system for organising data gathered for the coastal monitoring program. The relationship of primary data, locational information and the information system is illustrated in figure 2.1. The steps used to establish differential Global Positioning System (dGPS) techniques for field survey and incorporation of field data in an information system to service the monitoring program are described subsequently.

Inquiries into coastal management have repeatedly found widespread deficiencies in the knowledge available for management of coastal resources and in access to information by managers working in coastal environments. These difficulties have been specifically identified within the Alligator Rivers Region (Bayliss et al 1997). They have been identified through workshop and consultation processes with stakeholders and potential clients. A number of Commonwealth Government agencies collate natural resource data and have assembled information that is directly applicable to coastal and marine management. Efforts to obtain information from these sources suggests a need for capacity building and further data gathering in the van Diemen Gulf Region of northern Australia. The coastal monitoring program identifies measures to remedy these deficiencies.

Future research conducted as part of the monitoring program will seek to fill key gaps in knowledge of the various environmental attributes of areas that are particularly vulnerable to the effects of natural and human induced change. Targeting of research requires greater coordination of the research effort in the Region in general and of research effort leading to the development and implementation of management programs. Here, this is being achieved through establishment of a cooperative, strategic approach to data collection and management for assessment and monitoring of coastal change.

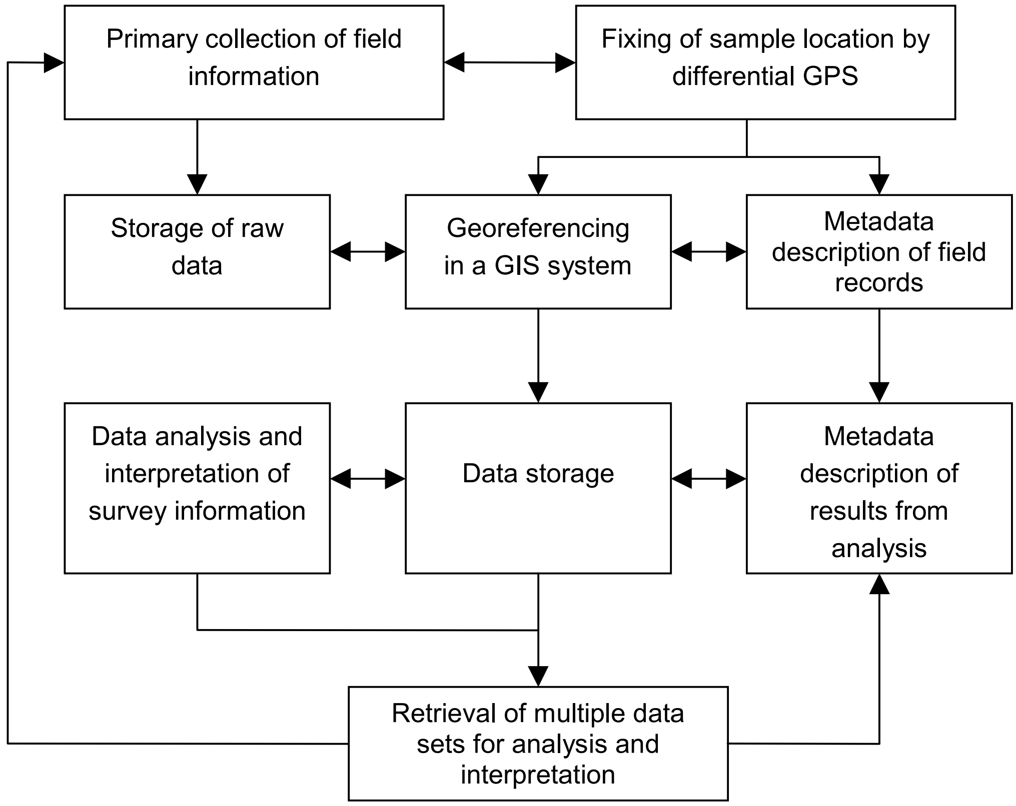

Figure 2.1 Data organisation, indicating the relationship of primary data, locational information and the information management system

2.2 Steps in the monitoring program

Steps in the monitoring program involve:

1. identifying and managing existing data sources;
2. monitoring the processes of change at a variety of spatial and temporal scales;
3. developing and applying information standards and archiving procedures; and
4. establishing and maintaining access, ownership and coordination of information.

Monitoring of processes occurring at a regional scale and development of a coordinated data management program were accorded the highest priority as all other projects in the monitoring program rely on them for context and integration. The program is being implemented in the following sequence:

- Establish a Geographic Information System structure for data collation, analysis and management.
- Establish and adopt standards for georeferencing of all information gathered, particularly in the field by differential GPS and other means of referencing to known coordinates.
- Acquire and deploy networks of: i) meteorologic, ii) oceanographic and iii) river gauging equipment for fully automated recording of processes operating at a regional scale.
- 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 tidal creeks of floodplains on the East Alligator and South Alligator River systems.
- From available vertical aerial photographs, estimate historical change in the distribution and community structure of mangroves along the coast and in the lower 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 change in the distribution of salt-affected vegetation communities on the floodplains of the East Alligator and South Alligator Rivers.
- Incorporate all spatial information and temporal descriptions in the Geographic Information System.
- Acquire bibliographic materials and collate information on data sets relating to integrated coastal zone management in the wet-dry tropics in a centralised metadatabase.

The projects comprising the monitoring program were in various stages of initiation and implementation at the time of writing. This document outlines their state of progress at the completion of program resourcing in February 1998. Consultation has continued between several agencies to ensure necessary standards for data acquisition are being maintained. This also ensures agency participation in the monitoring program has been maximised. The broad ranging nature of the program requires that agencies with existing skills and equipment are encouraged to contribute to its continued implementation and maintenance.

2.2.1 Identifying and managing existing data sources

Existing data sources include published literature, unpublished results of field research and spatial information in the form of remote sensing images, aerial photographs and maps. Although a considerable array of material is available, there has been no systematic audit of the material to determine whether it can be applied to questions arising from the issues relating to environmental change and the management of the Alligator Rivers Region.

Information on the Alligator Rivers Region is held by a number of Commonwealth and Northern Territory governmental authorities, as well as ERA Ranger uranium mine. Currently there is no directory to the custodians of the data to facilitate ease of access. Although there is a high level of cooperation between information holding bodies, access pathways are not always clear and there is a need to update contact points through a directory system. A number of issues relating to ownership and custodianship of the information will need to be resolved if material is to be more easily accessed and, where appropriate, incorporated into a Geographic Information System for the Region.

2.2.2 Developing and applying information standards and archiving procedures

The proposed data collection and monitoring programs are intended to provide a detailed account of environmental changes occurring at temporal and spatial scales affecting use and management of Kakadu National Park. In several instances the scales at which changes are occurring are not thoroughly understood and should be assessed in the early phases of the monitoring programs. Data collected should be sufficient to service numerical modelling and forecasting requirements. Both require establishment of rigorous standards for data acquisition that can be consistently applied to collection and collation of field and laboratory information.

Information loss has been a major concern for research and management authorities in the Region. Development of a metadatabase and a spatial bibliography are viewed as key tools for reducing future information loss. Inclusion of material in a metadatabase is needed urgently to provide a coordinated reference system for the wide range of research publications and unpublished data that has accumulated for the Alligator Rivers Region over the past 25 years. It should also be incorporated in a spatial bibliography to facilitate archiving and access. Compilation of a spatial bibliography requires coupling of a decision support (knowledge based) system with a Geographic Information System. Further, all spatial information gathered in the field should be georeferenced by the application of differential Global Positioning System technology and referred to an appropriate coordinate system.

2.2.3 Establishing and maintaining access, custodianship and coordination

Acquisition and custodianship of information has been recognised as a key area of issue within the Alligator Rivers Region. It could impinge on:

- the strategic management of the responses to environmental change;
- identification of research and monitoring needed to document the processes of change; and
- evaluation of the effectiveness of any management measures taken.

A wide range of specific questions arises under this area of issue, including:

- the value of existing and future data sources;
- accessing of data sources; and
- ownership of data and information pertinent to climatic and other environmental change.

Coordination of data and information acquisition has been identified as a key component of information management. The immediate need to develop a metadatabase is seen as being paramount for the information management process. The structure of the metadatabase is outlined in figure 2.2. Questions of access and custodianship can be addressed through the metadatabase protocols.

2.3 Status of the project

A data organisation system for the coastal monitoring program has been established by enhancement of skills for a range of field survey and data acquisition purposes by officers of the Environmental Research Institute of the Supervising Scientist. This involved acquisition and training in the use of differential Global Positioning System (dGPS) techniques and incorporation of the output from dGPS surveys in an existing geographic information system. Michael Saynor discusses these matters in Paper 1, ‘Using differential GPS techniques in environmental surveys’.

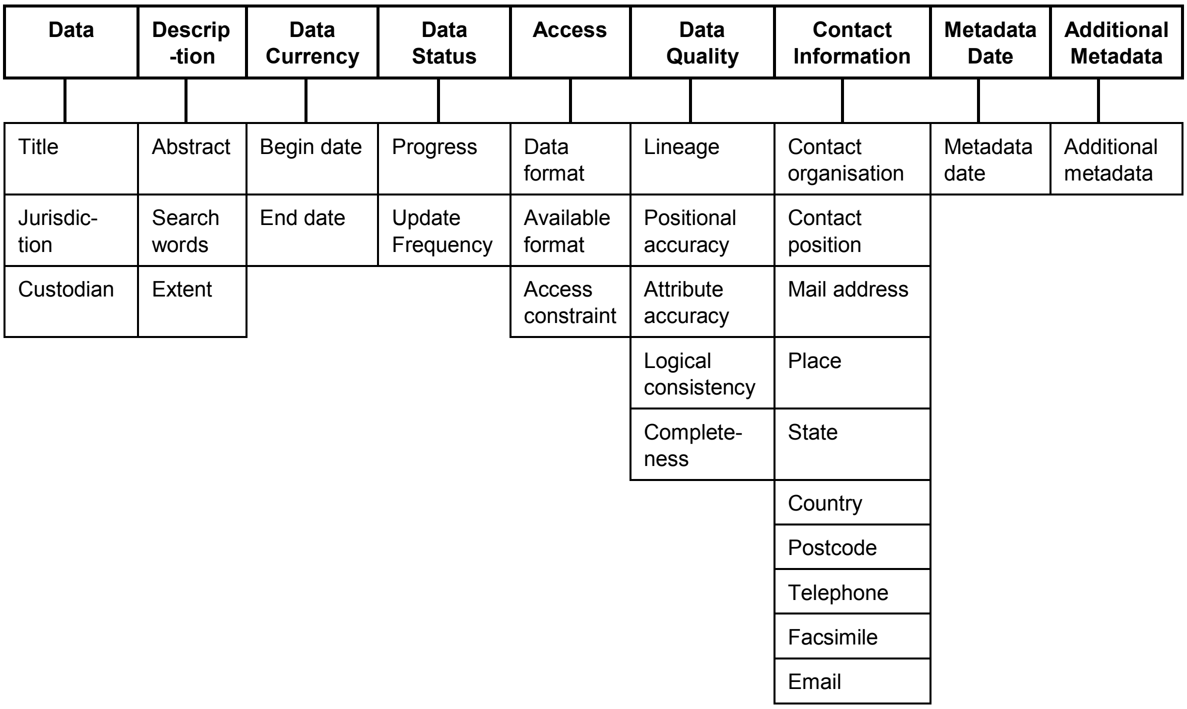

Figure 2.2 Structure of the metadatabase from Finlayson et al (1999a)

In turn, enhancement of the capacity to capture digital information through dGPS survey and other techniques, such as remote sensing and automatic recording systems, has raised pertinent issues concerning information management. Ann Bull has raised substantial issues relating to the archiving, storage, retrieval, and custodianship of data in her paper, 'Information Management'. There are problems that continue to require consideration by senior management of the Environmental Research Institute of the Supervising Scientist and by agencies with coastal management responsibilities in the Alligator Rivers Region.

Several streams of research undertaken by the Environmental Research Institute of the Supervising Scientist provide primary baseline information from which environmental change on the coastal plains might be assessed. Most of these are reviewed in Bayliss et al (1997). Although they do not specifically deal with the monitoring program, special reference should be made to the landscape and vegetation research reviewed in Finlayson and von Oertzen (1996), Finlayson et al (1998, 1999b), Storrs and Finlayson (1997) and a review of hydrologic research compiled by Erskine and Saynor (2000). These have been compiled since the vulnerability assessment of Bayliss et al (1997) was completed. They contribute to the baseline information upon which the monitoring program is founded.

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Paper 1 Using differential GPS techniques in environmental surveys

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Abstract

The Environmental Research Institute of the Supervising Scientist has developed a coastal monitoring program for the Alligator Rivers Region. The main aim of the program is to provide fundamental, scientific information that will benefit the people of the Region. In particular, it is intended that information gathered would contribute to more effective management of Kakadu National Park by defining areas of environmental change that are likely to affect its biophysical status and/or which may deleteriously affect current land use. Achievement of this aim requires adoption of standard procedures for referencing geographic information in the field and laboratory, use of rigorous techniques for information management, and development of procedures to ensure that the information is readily accessible to the client communities of interest.

The component of the coastal monitoring program described here outlines provision of survey support for georeferencing and storage of all spatial information as well as the collation of existing baseline information. A differential Global Positioning System was purchased to facilitate the development of an accurate georeferencing capability or monitoring framework for the Alligator Rivers Region. At the same time, a permanent Global Positioning System base station was established at Jabiru Airport to increase the accuracy of the differential Global Positioning System and extend its range of application in Kakadu National Park. Field surveys were undertaken to trial use of the differential Global Positioning System. The trials included mapping points of physical and biological interest, the alignment of tidal creeks and areas of wetland subject to salt water intrusion. Results achieved proved satisfactory for the intended purposes.

Establishment of differential Global Positioning System capability at the Environmental Research Institute of the Supervising Scientist has provided a basis for coastal monitoring projects as well as flexibility for mapping and georeferencing field sites for existing and future projects.

Key words: differential Global Positioning System, Alligator Rivers Region, Kakadu National Park, coastal monitoring

1 Introduction

The Alligator Rivers Region is a vast wilderness area (fig 1) with immense natural and cultural significance, some 150 km to the east of Darwin in the Northern Territory of Australia (Finlayson & von Oertzen 1996). The name of the Region is derived from its main rivers, the large South Alligator and East Alligator Rivers and the smaller West Alligator River and encompasses the 20 000 km^2 of Kakadu National Park.

Alligator Rivers Region

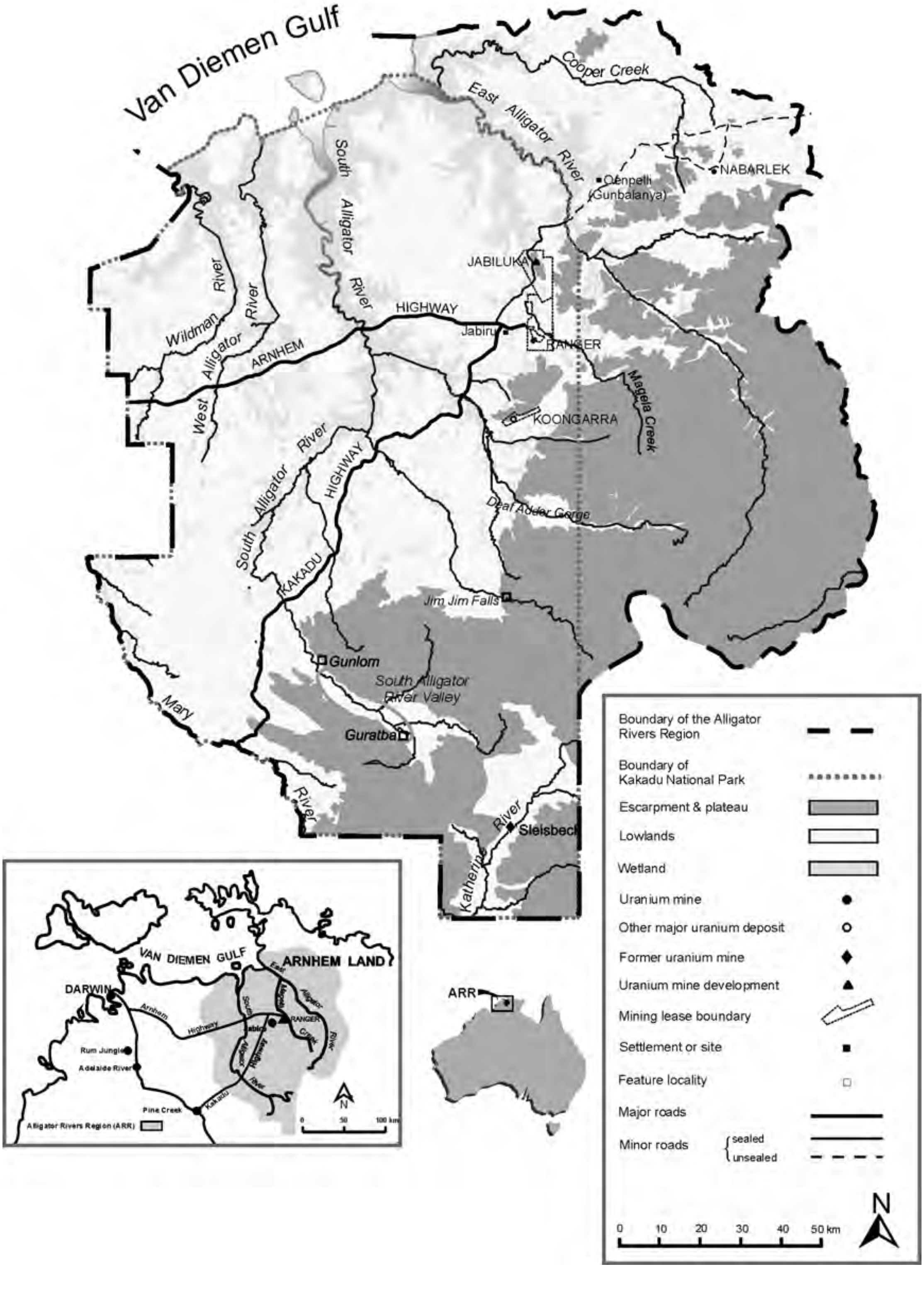

Figure 1 Location diagram for the Alligator Rivers Region

The Alligator Rivers Region extends southwards from van Diemen Gulf, through floodplains and lowland hills (Koolpinyah Surface) to the sandstone escarpment and dissected Arnhem Land plateau (Finlayson & von Oertzen 1996). The coastal margins and floodplains are low in elevation, making them susceptible to sea level fluctuation (Bayliss et al 1997). A baseline and a monitoring framework is required for this Region to ascertain the extent and effects of sea level fluctuation and climatic change.

2 Aim

A wide variety of environmental field survey and monitoring programs have been undertaken in the Alligator Rivers Region (Bayliss et al 1997), many as stand alone surveys. If these surveys are to be effectively linked for comparative or other complementary purposes, they need to have a common georeferencing standard. Hence, an initial aim of the Coastal Monitoring Program established at the Environmental Research Institute of the Supervising Scientist was to provide a survey framework for georeferencing and storage of all spatial information gathered in the program. This has been done in collaboration with the Portfolio Marine Group of Environment Australia and the Australian Surveying and Land Information Group (AUSLIG).

3 Objectives

Survey procedures for georeferencing information about the Alligator Rivers Region have been developed along with a capacity for a differential Global Positioning System at the Environmental Research Institute of the Supervising Scientist. The objectives in developing the capability are to:

- use a differential Global Positioning System receiver in conjunction with a GPS Base station established at Jabiru airport by AUSLIG, for field mapping and to establish biophysical survey locations in the field;
- locate pre-existing survey benchmarks and geodetic marks on and adjacent to the floodplains within Kakadu National Park. Select monitoring sites and establish new survey benchmarks for monitoring purposes;
- use existing benchmarks as well as establishing new benchmarks, to provide differential GPS control for kinematic mapping and position fixing in the field; and
- link all survey information to a Geographic Information System for spatial analysis and display.

4 Background

4.1 Differential GPS

Global Positioning Systems have receivers that collect signals from 24 satellites positioned in orbit by the US Department of Defence to determine positions on the ground and in the air. These satellites provide world-wide, continuous all-weather information to users, with the GPS requiring a minimum of four of the 24 satellites to accurately determine a position. GPS receivers use a coordinate system, known as World Geodetic System 1984 (WGS1984).

Differential GPS (differential Global Positioning System) 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 (benchmark) and the position of unknown points is determined relative to the reference point (Morton et al 1993). The Environmental Research Institute of the Supervising Scientist will use an Ashtech differential Global Positioning System, comprising a dual frequency receiver (Z-12) that is set up over known locations and a single frequency receiver (Reliance) that is used as the *rover* or mapping receiver.

Accuracy varies from sub-centimetre level to within 100 metres depending on how the signals are collected and processed. Rodgers et al (1996) report that GPS satellites emit 2 signals:

1. A high precision 'P-code' that provides centimetre accuracy and is reserved for the military; and
2. A C/A code that allows 25 m accuracy for civilian applications.

Accuracy using a single handheld receiver is usually in the 100 metre range. Better accuracy is achieved by using two or more receivers, one of which is set up over a known location. The use of a reference receiver at a known or surveyed location can reduce the error to obtain horizontal accuracy better than 5 m. However, vertical accuracy is 1.5 to 3 times worse than the horizontal, due mainly to the angle of the satellites. With highly sophisticated GPS equipment, accuracy in the order of a few centimetres can be achieved. This system is called a differential GPS. Blewitt (1996) discussed the precision of differential Global Positioning System measurements and concluded that at ranges shorter than 400 km between receivers the precision in distance measurements is several millimetres.

4.2 GPS base stations

In the early 1990s, AUSLIG established GPS base stations at eight geologically stable sites across Australia to detect plate/tectonic movement of the Australian continent. This was linked to the Australian Fiducial Network (AFN). The site positions are estimated to have an accuracy of 0.01 parts per million and will form a framework for the Geocentric Datum of Australia as defined in 1994 (GDA94). GDA94 is a new coordinate system which will be gradually implemented in Australia up to the year 2000. For all intensive purposes, it is the same as WGS84. GPS receivers at the AFN sites continuously record satellite data on their positions which is automatically returned to AUSLIG in Canberra for analysis (AUSLIG 1995). AUSLIG also maintain the Australian Regional GPS Network (ARGN), which is an extension of the AFN, and includes additional sites in Antarctica, New Zealand, Cocos Island and Macquarie Island (AUSLIG 1997).

One of the eight stable sites originally selected by AUSLIG was at Manton Dam, which is located 60 km south of Darwin. It is the only site in the Northern Territory and hence the closest to the Alligator Rivers Region. Since it was established, the Manton Dam site has been plagued with problems including:

- lightning strikes which resulted in equipment failure and caused large gaps in data, and
- data transference problems due to the remote locality.

In mid 1996, AUSLIG identified a number of sites possibly more suitable for the location of the AFN and ARGN GPS base station. Jabiru Airport was one such site. It was more thoroughly investigated by AUSLIG personnel in late 1996. During March 1997 it was agreed that the AUSLIG base station would be relocated from Manton Dam to Jabiru Airport where it could be monitored and maintained by the Environmental Research Institute of the Supervising Scientist staff. The establishment of the AFN and ARGN GPS base station means that the Alligator

Rivers Region is now serviced by accurate GPS baseline data which will increase the accuracy of any differential Global Positioning System used in the Region. Accuracies quoted by AUSLIG and Ashtech suggest that accuracy of ± 30 mm in the horizontal and ± 50 mm in the vertical should be achievable. Whilst the accuracy of differential Global Positioning System use in the Alligator Rivers Region is improved, the relocation of the Manton Dam GPS base station should not greatly disadvantage current users of the Manton Dam facility. The Environmental Research Institute of the Supervising Scientist has purchased GPS equipment compatible with that serving the base station at Jabiru.

4.3 Existing survey benchmarks and geodetic marks within Kakadu National Park

Three sets of survey benchmarks are available in the Alligator Rivers Region. They have been installed by the Commonwealth Government, the Northern Territory Government and ERA Ranger uranium mine. Additionally, lower-order survey marks have been established in scientific surveys of coastal mangroves by Hegerl et al (1979, 1981). The four sets required identification and reconciliation to a common datum to constitute the main component of the survey framework for the Alligator Rivers Region.

Commonwealth and Territory Government departments, as well as survey organisations acting on their behalf, often install benchmarks or geodetic survey marks to facilitate comprehensive surveys of surrounding areas. The marks, generally round plaques set into concrete, have been installed over many years. Approximately 23 000 have been entered into a national archive maintained by AUSLIG. The archive constitutes the National Geodetic Data Base (NGDB). It contains locations and elevations of benchmarks for a number of different coordinate systems and datums.

A search of the NGDB for the area bounded by latitudes 12ºS and 13ºS and longitudes 132ºE and 133ºE, corresponding to the northern part of Kakadu National Park, found 15 geodetic sites. The coordinates of these sites are listed in table 1.

Table 1 Coordinates for the sites found in the National Geodetic Data Base

Name		Latitude	Longitude	Easting	Northing	Height
U 573		-12 59 50.7426	132 45 41.5261	257198.5	8562077	16.965
U 659		-12 59 24.1102	132 18 29.7918	207995.8	8562419	125.1
Cahill	NTS 419	-12 51 58.7381	132 42 12.5753	250769.6	8576530	152.99
Kapalga	NTS 018	-12 42 33.2344	132 26 3.3034	221360.6	8593641	110.6
Wildman West	NTS 016	-12 41 17.3466	132 2 18.4354	178318.2	8595518	95.6
Wildman East	NTS 017	-12 39 23.6371	132 8 13.2606	188993.9	8599134	86.7
U 571		-12 37 35.9186	132 0 15.1760	174518.1	8602286	21
Magela	NTS 019	-12 31 53.3246	132 59 22.4298	281542.2	8613839	300.7
U 539		-12 29 57.6687	132 44 40.4187	254877.5	8617179	31
U 689		-12 28 47.5668	132 29 19.8213	227049.6	8619083	12.6
Malangheri Hill	NTS 530	-12 26 2.6658	132 57 53.0492	278760.5	8624596	62.88
Cannon West	NTS 575	-12 22 33.8789	132 56 4.5772	275434.2	8630987	92.55
U 815		-12 16 52.8258	132 12 12.9557	195793.9	8640751	91.32
Cairncurry	U 570	-12 8 1.5296	132 30 46.1828	229304	8657415	4
Field Is	U 563	-12 5 19.0950	132 21 4.2150	211650	8662244	4

The Northern Territory Department of Lands, Planning and Environment (DLPE) was contacted regarding benchmark or levelling information along the major roads of Kakadu National Park. Along the Arnhem Highway benchmarks are located at approximately 5 km intervals. There are also some benchmarks located along the road to Gunbalanya (Oenpelli). The Kakadu Highway has not been investigated as it is runs mainly through the southern part of Kakadu National Park away from the coastal areas. Locality diagrams have been obtained for some of the benchmarks, and include height information in Australian Height Datum (AHD) and descriptive details, but no coordinate information. Many of the benchmark sites are located under trees and may not be suitable for the establishment of a remote base station receiver. However, they do provide very accurate height data, which could be used to visually survey (using a theodolite) a nearby mark that is being used for a base station location. Information was also obtained from DLPE with regard to benchmarks within the boundaries of Jabiru township.

ERA Ranger Uranium Mine (RUM) has approximately 12 benchmarks in and around the mine lease which they use as markers for aerial photographs and digital terrain mapping determinations. These are in Australian Map Grid (AMG) and were relocated and painted by RUM personnel for aerial photography that was flown in July 1997. These may be useful, however, they are mostly within 10 km of the AUSLIG GPS base station at Jabiru Airport, and hence less useful than those further afield

Hegerl et al (1979) established 25 survey sites along the coast of Kakadu National Park. The sites mark transect lines for a biological inventory of mangrove forests and tidal marshes. A map of the sites is available, and their approximate locations known from the map. The biological transects are detailed. Hence Hegerl et al (1979) provide an important baseline from which more recent change can be ascertained. Unfortunately, specific reference to the positioning of transect lines is obscure and the field notes apparently have been lost. A task for the Environmental Research Institute of the Supervising Scientist will be to source the original survey references and relocate the survey lines with differential Global Positioning System.

A benchmark register for the Alligator Rivers Region has been set up at the Environmental Research Institute of the Supervising Scientist. A working document has also been created. It contains appropriate documentation regarding the usefulness of the various benchmarks. Information on subsequent benchmarks that are established or found will also be placed on the register, with documentation added to the working document.

5 Use of differential Global Positioning System in environmental survey

Digital GPS has become increasingly recognised as a useful tool for environmental field surveys (Blewitt 1996). This section gives a brief description of some uses of differential Global Positioning System as well as a more detailed explanation of the initial work by officers of the Environmental Research Institute of the Supervising Scientist using the differential Global Positioning System.

5.1 Where has differential Global Positioning System been used

Differential GPS has been used for a variety of applications in environmental surveys. Morton et al (1993) conducted field experiments on a 2 km stretch of sandy beach at Galveston Island State Park, Texas, United States of America. They evaluated GPS survey techniques for monitoring beach profiles and concluded that GPS surveys are suited to this application because of superb positioning techniques and greater utility compared to other available techniques. Liu and Brantigan (1995) reported on the accuracy and efficiency of differential Global Positioning System used in forest environments in Canada. They also concluded that differential Global Positioning System was an accurate and cost effective method (mapping tool) for determination of area when used in forest traverse survey. A compact hand-held data-logger linked to a differential GPS has been used to map weeds in the United Kingdom by Stafford et al (1996). This system achieved an accuracy of 1–3 metres in the horizontal plane. This was sufficient for mapping purposes given that they were not interested in changes of elevation.

In Australia, Port Stephens Council, New South Wales, has purchased a differential GPS (AUSLIG 1996) and has obtained real time accuracy to 5 metres when mapping and locating assets in the Shire. Some tertiary educational institutions, such as Curtin University and the University of Western Australia, have acquired differential Global Positioning System systems and are incorporating GPS techniques in their teaching and research programs. Differential Global Positioning System is also used by mineral exploration companies and mining companies to explore for minerals and map mining leases and sites.

5.2 Use of differential Global Positioning System at the Environmental Research Institute of the Supervising Scientist

The differential Global Positioning System at the Environmental Institute of the Supervising Scientist uses Ashtech equipment. It is controlled and analysed by Reliance or Prism 2 software. The data is post-processed, ie after the fieldwork has been completed, and does not have a real time facility. It is necessary to recognise three components or features of the environment before using differential Global Positioning System as a mapping and georeferencing tool: points, lines and areas. For example:

- *Point Features* — refer to points or locations in the environment such as soil sample locations, transect points, road sign locations;
- *Line Features* — refer to boundaries or other linear features in the environment such as transect lines, woodland boundaries, dry creek beds; and
- *Area Features* — refer to areas or spatial features such as areas of dead trees, water bodies.

It is necessary with these features to ensure that they are completely traversed around, as this is a polygon feature that will join the first and the last readings together by a straight line.

The features that are likely to be present at each study area are determined prior to starting field measurement and a feature file is downloaded to the rover receiver. In the field the base station receiver (Z-12) is established over a known location, such as a geodetic point or bench mark. The rover antenna (and receiver) is mounted on some sort of vehicle (quad bike, car, boat) or carried around either on the staff post or in a back pack.

At the conclusion of the field work the data is downloaded from the receivers and processed, producing a map in Reliance software. This processed data can be exported in various forms, such as comma delimited text files (.txt) for use in word processing documents and spreadsheets, and generate files (.gen) for import into GIS software as well as other forms.

Initial use of differential Global Positioning System at the Environmental Research Institute of the Supervising Scientist has been to map areas of salt water intrusion and tidal creek extension at several sites, such as Point Farewell, Munmarlary and Kapalga in the Alligator

Rivers Region (fig 2). The differential Global Positioning System was also used to georeference sample sites at the rehabilitated Nabarlek minesite. As these were the first areas mapped using the differential Global Positioning System it was very much a learning and trial phase as well as a teaching exercise. Results from the initial surveys are outlined below.

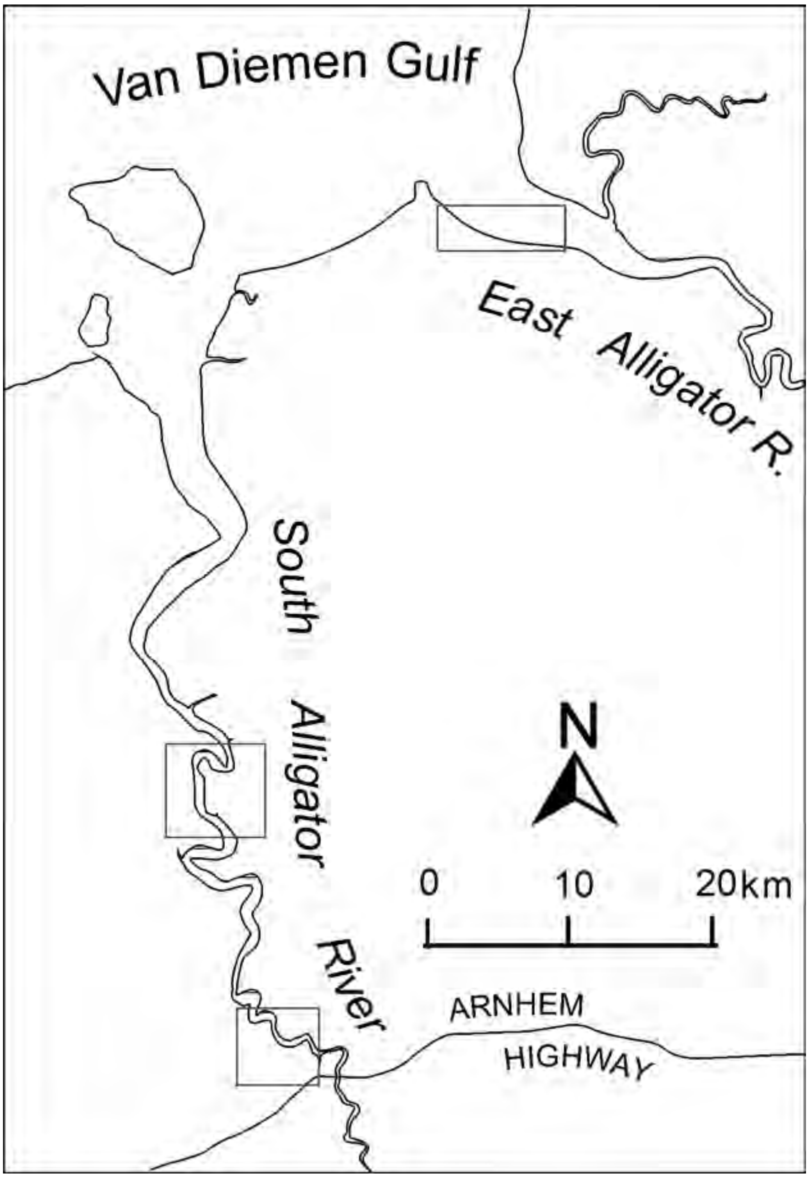

Figure 2 Sites where the differential Global Positioning System was used

5.2.1 Point Farewell

The differential Global Positioning System was used to map the present morphological and biological features of an area near Point Farewell to establish an accurate (georeferenced) environmental baseline (or starting point) from which ongoing monitoring can proceed in future.

Point Farewell was the first field site where the Environmental Research Institute of the Supervising Scientist differential Global Positioning System was used as a mapping tool. The site (fig 2) is located on the southern coastline of van Diemen Gulf in the estuarine funnel of the East Alligator River (Chappell & Woodroffe 1985). This site was selected after Jonathan

Nadji (Traditional Owner) approached the Environmental Research Institute of the Supervising Scientist to investigate areas of dead *Melaleuca* forest near Point Farewell. Examination of aerial photographs for the years 1950 to 1991 revealed evidence of rapid extension of tidal creeks and colonisation of them by mangroves (Cobb 1997). The environmental changes have resulted in saltwater incursion into areas of fresh water.

Field work was completed over several days using the rover receiver mounted on a quad bike in conjunction with the base station receiver. A temporary benchmark was established as a base station at the beginning of the field work as there was no existing bench marks nearby. This position was marked by a 2 m star picket driven 1.2 m into the ground. Spatial information was provided by recording the data as the quad bike was driven around areas of biophysical interest, such as stands of mangroves, dead trees and salt flats. When more accurate vertical data (elevation) was required, the quad bike was stopped, the engine cut and a point reading taken. The field data was subsequently entered into the GIS at the Environmental Research Institute of the Supervising Scientist. A map of the processed information was produced (fig 3).

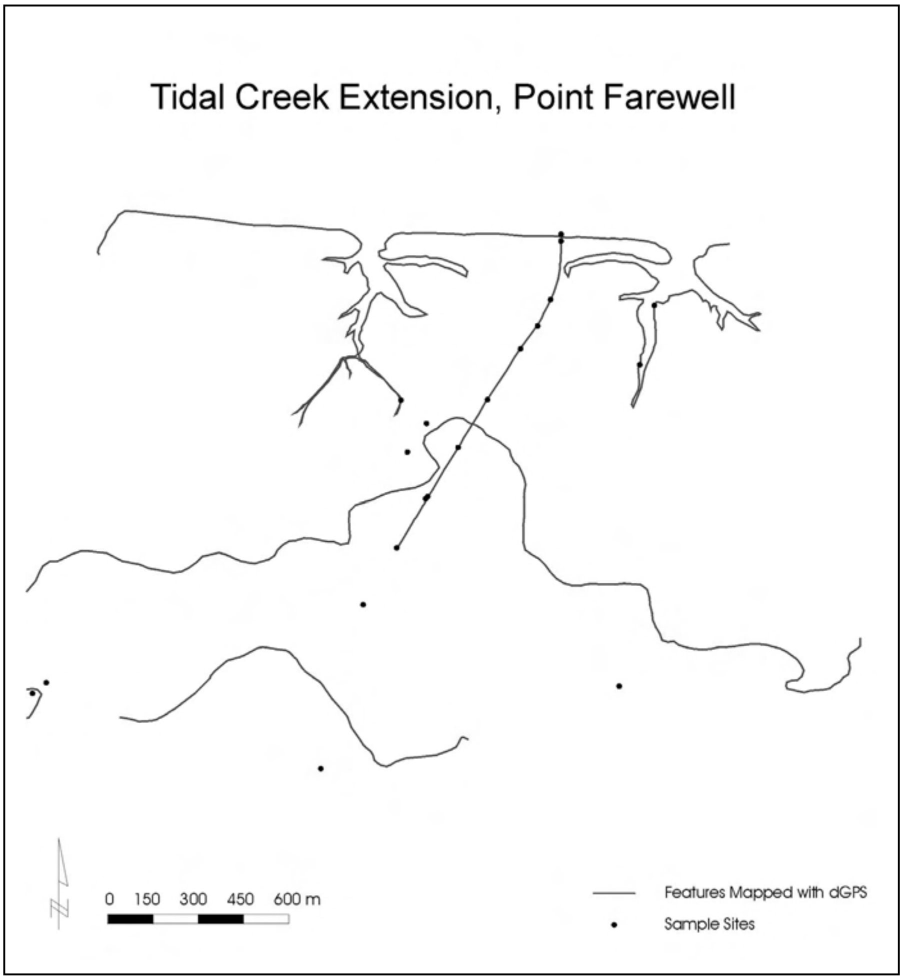

Figure 3 Differential Global Positioning System map of various features at Point Farewell

5.2.2 Kapalga

An area of dead *Melaleuca* woodland on the South Alligator floodplain near Kapalga was suggested for investigation by CM Finlayson (pers comm). This area is located on the cuspate bends (Chappell & Woodroffe 1985) of the South Alligator River, approximately 55 km (straight line distance) from the river mouth. Examination of aerial photographs for the years 1950 to 1991 (Cobb 1997) indicated extension of one main tidal creek network into a freshwater swamp, resulting in *Melaleuca* dieback.

The differential Global Positioning System was used to extensively map the area of dieback using similar methods to those mentioned above. An AUSLIG trig station (geodetic site) was located on a nearby hill (Kapalga NTS 018) and was used as the base station location. The roving station was then used to determine the boundary of area affected by saltwater incursion. Kapalga was visited on several occasions due to ease of access and its close proximity to the Environmental Research Institute of the Supervising Scientist. The area mapped is illustrated in figure 4. It provides a baseline from which future change can be determined.

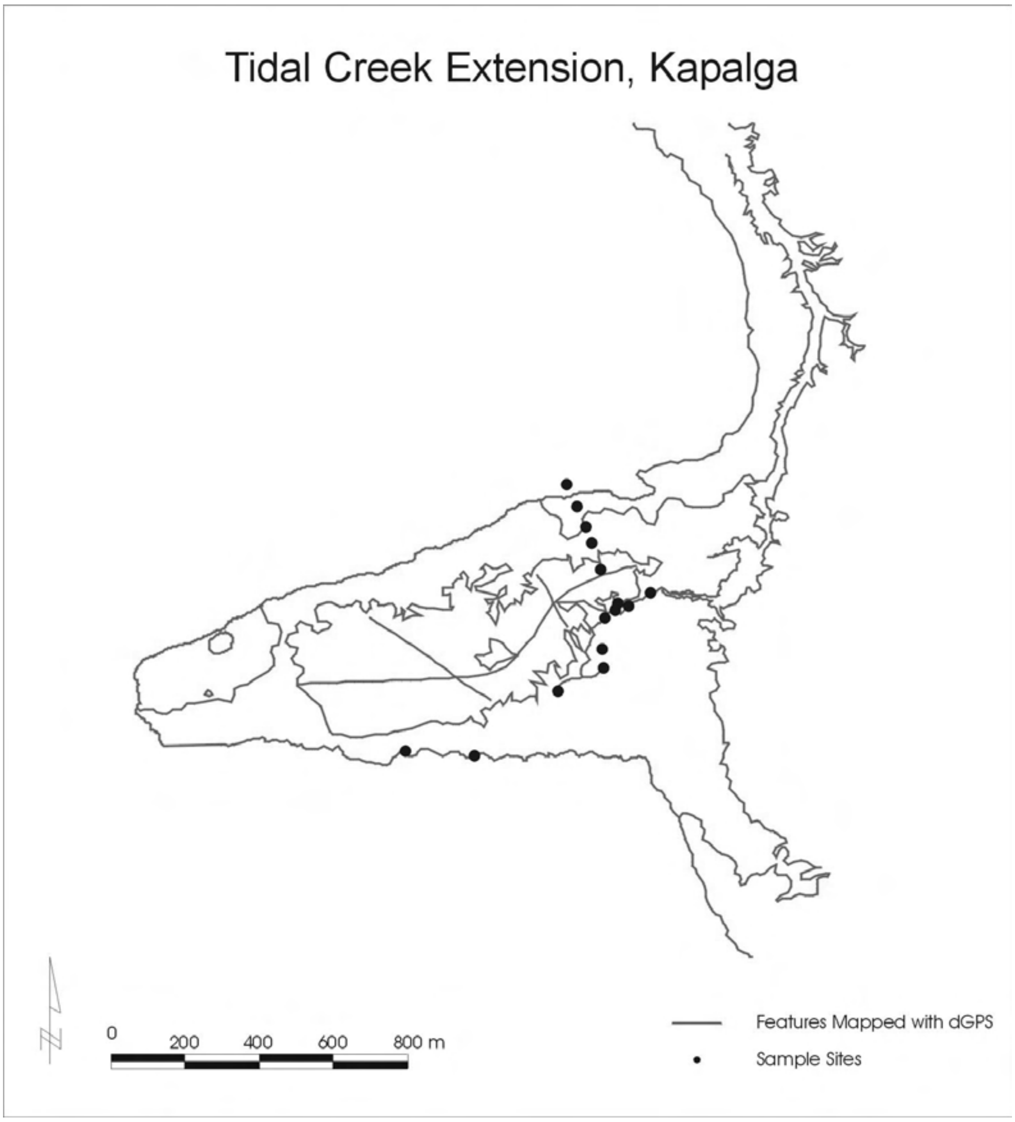

Figure 4 Differential Global Positioning System map of various features at Kapalga

5.2.3 Munmarlary

Munmarlary was selected by Cobb (1997) after examination of aerial photographs for the years 1950 to 1991. The photography indicated extensive growth of tidal creeks and mangrove encroachment within the confines of a palaeochannel swamp on the left (west) bank of the South Alligator River whilst there was little evidence of the trend occurring on the right (east) bank. Access to the left bank of the tidal creek was difficult so field mapping using the differential Global Positioning System was conducted on a tidal creek extending from the right bank. Aerial photographs indicated that the creek selected was stable, but mangrove colonisation had increased since 1950.

An existing benchmark next to the airstrip near the old and disused Munmarlary homestead (U 689) was used as the base station. The creek boundaries and mangrove extent were mapped using the rover installed on a quad-bike. The processed GIS map is shown in figure 5 and will be used as the environmental baseline for future monitoring.

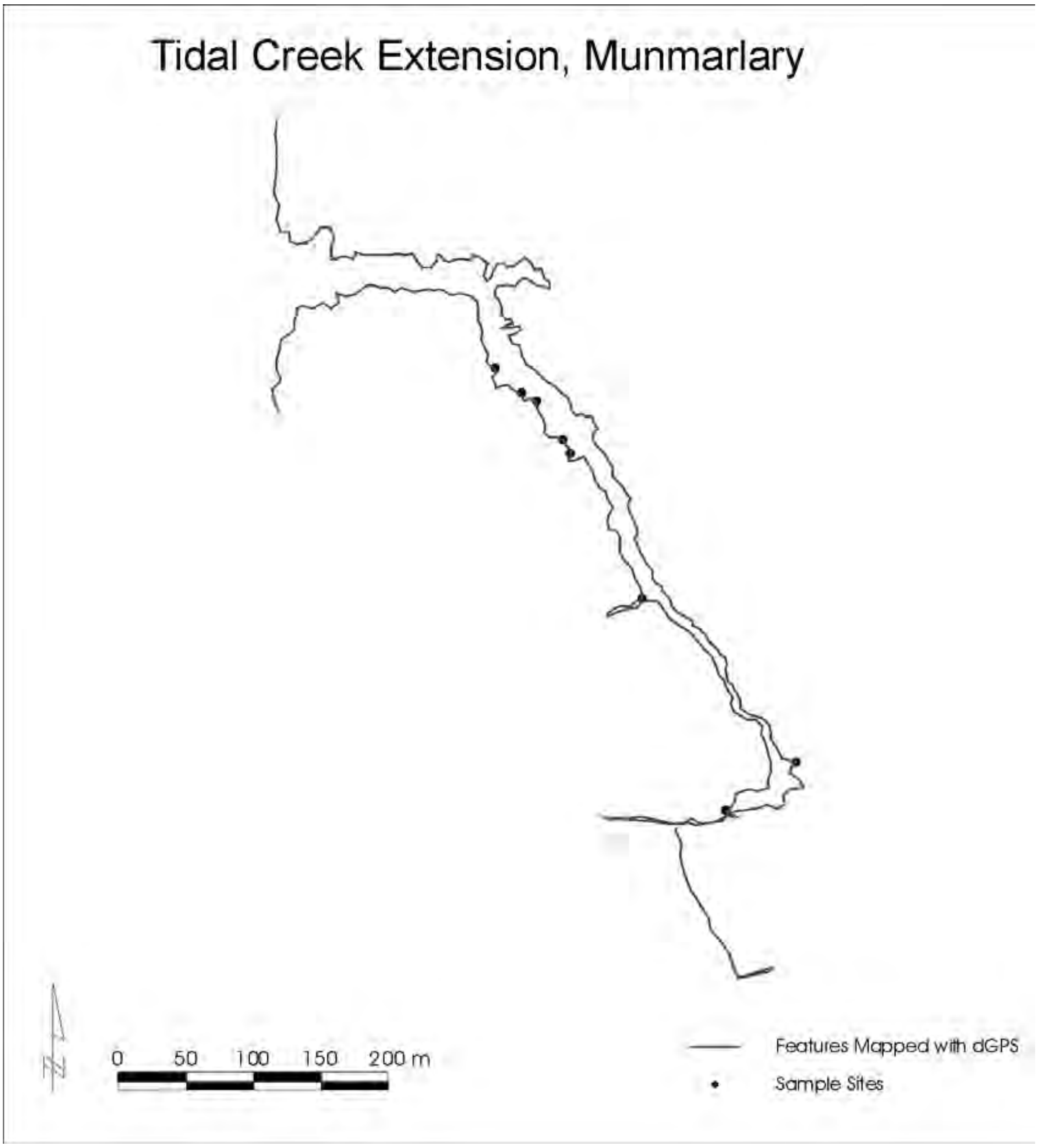

Figure 5 Differential Global Positioning System map of various features at Munmarlary

6 Outcomes and recommendations

Development of a coastal monitoring program and a framework for coastal monitoring in Kakadu National Park has been contingent on the establishment of a differential Global Positioning System system for accurate georeferencing and mapping. This has been achieved by completing the following:

- purchase of differential Global Positioning System equipment that is compatible with AUSLIG equipment;
- relocating the AUSLIG GPS base station to Jabiru Airport;
- documentation of procedures for using differential Global Positioning System and linkage with GIS capability and staff training (Saynor in prep); and
- locating existing benchmarks and establishing additional bench marks in Kakadu National Park.

Completion of these tasks has provided the Environmental Research Institute of the Supervising Scientist with an accurate field mapping capability. This is not only an extremely beneficial tool for the coastal monitoring program, but for many other Environmental Research Institute of the Supervising Scientist projects as well. It has wider applications, but these need to be discussed with the interested parties as required.

Although the tasks and outcomes mentioned above have been completed, and an initial coastal monitoring framework put in place, this program could be further enhanced by:

- locating benchmarks and geodetic marks that documentation and locality plans indicate as existing, but have not yet been found;
- determining if other benchmarks or geodetic marks exist, obtaining locality plans and station summaries, and documenting the existence, usefulness and accessibility of such sites. Suggested possible sites include, Kakadu Highway and sections of the Arnhem Highway, two bridges over the South Alligator, and areas adjacent to Kakadu National Park, including Arnhem Land that might have some form of benchmarks. The transect locations used by Hegerl et al (1979) also require field identification and location;
- establishing regular aerial photography and/or video coverage of key coastal and wetland areas in Kakadu National Park at regular (2–5 year) intervals. These should be properly groundtruthed and georeferenced to enable easy rectification and entry to GIS systems such as that established at the Environmental Research Institute of the Supervising Scientist. This would be an expensive exercise and could require collaboration with other parties, such as Parks Australia North;
- where possible, rectify historical aerial photographs using the differential Global Positioning System;
- investigation of methods of obtaining information from remotely sensed data such as Radarsat, Airsar, Landsat, Spot, that could be used as monitoring tools. Analysis of different time series could be used to show and monitor changes;
- establishing capability with Prism 2 software as it provides more accurate differential Global Positioning System information. This would allow recently established remote field base stations to have their coordinates accurately determined by using the AUSLIG base station located at Jabiru Airport; and
- continuing with environmental baseline projects as well as additional projects yet to be identified.

7 Conclusions

Establishment of a differential Global Positioning System at the Environmental Research Institute of the Supervising Scientist has provided flexibility for mapping and georeferencing field sites for existing projects and any number of future projects. It has provided a survey framework for baseline monitoring and has enabled the Environmental Research Institute of the Supervising Scientist to develop the capacity to locate, map and georeference geomorphic and biologic features in the Alligator Rivers Region. The differential Global Positioning System has successfully been used to map various features such as saltwater intrusions, mangroves, wetland areas, basin cross-sections, and tidal creek extensions.

Establishment of a differential Global Positioning System capability and its linkage with GIS to store the information were identified as the main tasks to establish a survey framework for the coastal monitoring program in the Alligator Rivers Region. Completion of these tasks has provided the means by which research or study areas could be accurately georeferenced. This allows the development of baseline data which could be used to assess and monitor change in the future. It is particularly pertinent with the possibility of greenhouse gasses causing global warming and potential sea level rise.

8 Acknowledgments

Thanks are owed to many people. The development of a Coastal Monitoring Program in the Alligator Rivers Region was funded by the Portfolio Marine Group of Environment Australia. Parks Australia North staff allowed access to the many sites and provided other information as required. Martin Hendy (AUSLIG) has provided valuable help and words of encouragement when differential Global Positioning System equipment has been causing trouble. Ray Hall undertook various tasks including, data acquisition, liaison with government and private organisations. Gary West and Alex Bakunowicz, Department of Lands, Planning and Environment and Lyall Camp AUSLIG, provided information on benchmarks. The work of a multitude of field assistants, Ray Hall, Ann Bull, Ben Bayliss, Stephanie Cobb, Darren Bell, is also gratefully acknowledged. Diagrams were provided by Ben Bayliss and Ann Bull.

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Paper 2 Information management

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Abstract

The Environmental Research Institute of the Supervising Scientist established a Coastal Monitoring Program in 1996 to assess and monitor coastal change in the Alligator Rivers Region of the Northern Territory, Australia. The program included several projects examining environmental change in the coastal wetlands of the Region by employing a variety of methods and at a range of scales. These projects have the potential to generate significant quantities of information such that the program requires information management of a high standard. Information management is becoming increasingly recognised as a complex and poorly handled component of research. Design and implementation of an efficient information management system is necessary to identify the information that will be collected and generated as a result of the research; describe the systems, practices and resources required to manage the information successfully; and to gradually implement these systems.

The major types of information identified as emanating from the program include documents, spatially referenced information, time series and remotely sensed imagery. This diversity in data source, form and intended use has significant implications for design of an information management system. The design of a two tiered approach to metadata will enable comprehensive project level and dataset level metadata to be maintained. The management tools required to implement an information management system for the program will consist of a framework for data and information management combining hardware, software and other storage systems and archives. These systems require considerable resources for their development and implementation. The gradual implementation of an information management system for the program is now occurring, with the development of a fully functional geographic information system, project level metadatabase and extensive filing system having already taken place.

Key Words: information management system, metadata, Geographic Information System, coastal monitoring program, northern Australia

1 Introduction

Information management within organisations is a complex issue — often one to which few resources are allocated and insufficient recognition afforded. Information management has become a scientific discipline in itself and can no longer be considered the sole domain of the librarian or information technologist. In the computer era, it has become easy to generate and store huge volumes of information. However, efficient and effective information management systems are required to manage and maintain the corporate knowledge of an organisation (Institution of Engineers 1993). In many research and environmental management agencies corporate knowledge represents the major asset of the organisation. Currently, many such organisations are employing data managers and establishing groups responsible for the provision of systems and protocols to assist others with information management. For example, the Environment Resources Information Network (ERIN) within Environment Australia serves as an information manager. Additionally, it is now possible to attend conferences dedicated to information management, eg the Northern Australian Remote Sensing and GIS conference (Riley et al 1993), NARGIS (1995), NARGIS (1997) and NARGIS (1999). The challenge for environmental research and management agencies is to develop a capacity to efficiently collate, store and retrieve information in their own organisation while facilitating ease of information exchange between agencies.

The need to develop directories (or metadatabases) for spatial data has been recognised for some years and a considerable amount of work has been devoted to this at a national and international level. A number of organisations are concerned with information and data management as well as the development and distribution of standards, both in Australia and internationally. These organisations are mainly concerned with the management of spatial and GIS data, however, many of the principles apply to other data types. In Australia, information management has involved organisations such as the Australia New Zealand Land Information Group (ANZLIC), the National Resources Information Centre (NRIC) and the Environmental Resources Information Network (ERIN). Internationally, the major groups contributing to establishment of metadata standards include the US Federal Geographic Data Committee (FDGC), the International Organisation for Standardisation (ISO) — technical committee on geographic information (ISO TC211), the American National Standards Institute (ANSI), the US National Biological Information Infrastructure (NBII), the World Conservation Monitoring Centre (WCMC) and the newly created European Spatial Metadata Infrastructure (ESMI). These groups have produced metadata standards for spatial metadata which are incorporated into current national data directories.

In addition, organisations such as the CSIRO Marine Research Data Centre (www.marine.csiro.au/datacentre/) have been established to assist scientists and managers with data and information management within the organisation, and are producing protocols and systems for internal use. These are primarily concerned with internal management of spatial data. However, many of the general principles adopted are also applicable to non-spatial data generated by the Environmental Research Institute of the Supervising Scientist and other organisations. Within Environment Australia, the Biodiversity Group has developed guidelines for data management and use. These are applicable to the Environmental Research Institute of the Supervising Scientist.

Research in the field of environmental management requires the collection, storage and analysis of a substantial range of information (Panizza et al 1995). This is well demonstrated by the activities of the Environmental Research Institute of the Supervising Scientist which has been collecting data for a single discrete region for more than 15 years (Bayliss et al 1997, Finlayson & Bayliss 1997). Effective information management within an organisation such as the Environmental Research Institute of the Supervising Scientist requires a solid corporate database and a user friendly system. This is analogous to a library where the books and publications constitute the data and information and the catalogue is the metadatabase. Library users access the catalogue to make effective use of the information resource. The database should be flexible and able to store many different types of information in different modules.

Increasingly sophisticated information technology has proved to be a ‘double edged sword’. Information technology facilitates information management and makes it easy to generate large amounts of data and hundreds of files. Commonly these are stored with no explanatory documentation. Overall, the importance of maintaining adequate records and documentation is becoming increasingly important in the information age. This document discusses the information management requirements of the Environmental Research Institute of the Supervising Scientist in the context of the Coastal Monitoring Program. The first section discusses the background and progress at the Environmental Research Institute of the Supervising Scientist towards a metadatabase and an operational Geographic Information System. The latter part describes the issues being considered and solutions being adopted for the Coastal Monitoring Program to ensure effective information management.

The Environmental Research Institute of the Supervising Scientist initiated the Coastal Monitoring Program in October 1996 to assess and monitor coastal change in the Alligator Rivers Region of the Northern Territory. The program examining coastal change used a variety of methods and was conducted for a range of scales. Hence, information management is essential for the Environmental Research Institute of the Supervising Scientist to continue production of quality outputs within reasonable timeframes. Design of a proficient data management system will provide staff with the means to easily access corporate data holdings and information. The general aim of this facet of the program was to provide guidelines for management of all information and meta-information collected and collated during the course of this program and contribute to improved overall information management at the Environmental Research Institute of the Supervising Scientist. More specific objectives are outlined below.

1.1 Project framework

1.1.1 Nature of the Coastal Monitoring Program

The Coastal Monitoring Program includes several mapping and monitoring projects specific to environmental change in the wetlands of the Region (Eliot et al 1999). It combines historical and recently collected information from many different sources and disciplines (Bayliss et al 1997, Eliot et al 1999). New and existing data both from the Environmental Research Institute of the Supervising Scientist and other organisations will be collated. Therefore, it is of paramount importance that data and information management practices become part of the program from the beginning. Individual projects have the potential to generate significant quantities of information. The major types of information which have been and are expected to be generated during the program are spatial data, bibliographies, tabular data and text information such as reports and scientific papers. Successful implementation of the program requires that this diverse assemblage of project information is maintained within the one framework and is associated with common goals and shared outcomes. In order to achieve these goals it is necessary that all information is collected, collated and stored within a clearly structured information management system. Extensive planning is required to ensure that an appropriate level of flexibility is retained by the system to allow the addition of new forms and sources of data. Specific consideration must also be given to the storage and access of time series data, as it is important that all information can be compared and used in conjunction with previous data.

1.1.2 Historic practices

Historically, information generated by research projects has been produced and stored in the form of written reports. Many of these reports contain tables composed of raw or processed data and illustrative material. These have been archived in filing cabinets, on shelves and collated in libraries. Unpublished works commonly remain with the author or at the institution where the research was undertaken. More recently there has been a trend towards storing information in digital format on hard disks, CD-ROMS, tapes and floppy disks. However, there are many different formats in which data can be stored, both in terms of hardware and software. This can both create and alleviate information management problems. For example, individuals at the Environmental Research Institute of the Supervising Scientist may have raw data stored in a combination of several different spreadsheets, text documents or databases. This information may be stored on computer or be present as hard copy files.

Most organisations dealing with land management or ecological research now have a GIS capability. The Environmental Research Institute of the Supervising Scientist has recognised for some time the need to have a GIS to store and analyse geographic information as part of its research program. The Environmental Research Institute of the Supervising Scientist now has a functional GIS database including hardware, software and data. The hardware platform is a Sun Ultra workstation with 12 Gbytes of external disk and a 14 Gbyte tape drive to facilitate data transfer and backups of the system. The software being used is ArcInfo and Arcview. This software was originally selected because it is being used by the rest of Environment Australia and particularly by the Environmental Resource and Information Network. Some other groups within Environment Australia are also using MapInfo as a user-friendly package which meets the needs of many users. It does not, however, have the facilities that ArcInfo offers in terms of data editing and analysis. The ArcInfo and Arcview software at the Environmental Research Institute of the Supervising Scientist are unix versions and are running on the Ultra workstation. These will be accessed by users on the PC network through the use of terminal emulation software.

Data holdings include the major base datasets which are obtained through the Environmental Research and Information Network and include topographic data, digital elevation models, census data, land tenure data, fauna and flora records, climate surfaces, geology, soils and administrative regions. Although this data is useful for many purposes, the continental scale means that it has limited uses for a number of regional projects.

Other data holdings include some data which has been acquired from Northern Territory Government agencies and Parks Australia North. For some time Parks Australia North had their own GIS system stored in Environmental Review and Management System (Ryan et al 1995). However, they are now translating and recovering much of the data into ArcInfo and MapInfo formats in order to integrate the data with that held in the rest of Environment Australia. This integration is also occurring with satellite imagery. The Environmental Research and Information Network now holds a catalogue of most of the satellite imagery which has been purchased by various sections of Environment Australia and is holding copies of the data. This catalogue can be accessed via the WWW (http://www.environment.gov.au/psg/erin/index.html).

Work is continuing on integration of data from the different sources and the updating of collated data. For example, much of the data from Parks Australia North is incompletely attributed and requires substantial rectification. Essentially there is no metadata available for the majority of this data and it is in different coordinate systems. In addition, much of the new information being collected is at a local scale and is incompatible with the topographic data for reasons of scale and accuracy. For example, the scale of topographic map data being used is 1:250 000. It was collected using an outdated datum and has a horizontal accuracy of 25 m. The differential GPS being used by the Environmental Research Institute of the Supervising Scientist to collect data has a horizontal accuracy of less than 1 m, which is an order of magnitude better than information from the topographic maps.

1.1.3 Bureaucratic framework

The Environmental Research Institute of the Supervising Scientist sits within the Supervising Scientist Division of Environment Australia and is bound by standards and practices for information management adopted by the Department. Hence, principles and practices adopted by the Environmental Research Institute of the Supervising Scientist with regard to information management are developed in consultation with relevant groups in Environment Australia. This ensures future developments are consistent with the rest of the department. Standards can be provided to facilitate data exchange and incorporation of metadata into national data directories.

2 Aims

The aims of the information management component of the Coastal Monitoring Program are to:

- identify the information that will be collected and generated as a result of this project,
- describe the systems, practices and resources required in order to manage the information effectively and efficiently, and
- gradually implement these systems, depending on available resources.

3 Methodology

3.1 Types of information

The Coastal Monitoring Program includes a considerable variety of research projects, from the dGPS mapping of tidal creeks to large-scale climatological and oceanographical studies. Its major components have been reviewed by Saynor et al (1999).

3.1.1 Data

Methods and processes required to capture, store, retrieve and manipulate the datasets resulting from the projects are diverse. They range from individual spreadsheets and statistical analysis to spatial databases and visual analysis. Furthermore, datasets emanating from the Coastal Monitoring Program will include both digital and non-digital forms of data. This diversity in data source, form and intended use has significant implications for the design of an information management system. It is therefore important to identify and categorise data generated by the program based on similarities in their storage and access requirements. The major types of information that will be collected and/or generated have been identified. These include:

- Documents — both hard copy and digital
- Spatially referenced information — including GIS coverages, survey data and maps
- Time series — measurements or other data collected at a number of different points in time
- Images — including satellite imagery, aerial photographs, photographs and slides.

However, within these groups, consideration must be given to the inherent variability of each dataset and how this will impact on the individual data storage requirements. For example, satellite imagery can consume vast amounts of disk space when stored on-line. It may require storage in a different manner to other digital forms of imagery, such as digital photographs. The development of an archiving system for some data types may be necessary due to the large quantity of data being gathered. Protocols that outline various types and formats of data to be handled within the system should be developed and implemented. This ensures that archived data are maintained and accessible within the system.

3.1.2 Metadata

Metadata is defined as data about data. In other words, it is information which describes a dataset — what it contains, who collected it and why, the geographic extent and other characteristics of data. It is used to locate and understand data (USGS 1994). A metadatabase is like an index or catalogue of datasets. The data being described can be a project, or it can be a single dataset such as a collection of plant records or the results of a fauna survey. Metadata does not need to have a spatial component, although spatial data and the people who deal with spatial data are presently leading the way as far as development of metadatabases are concerned. The main reason for this appears to be that with the advent of GIS systems and easy transfer of computerised data, metadata took on a new significance with the exponents of GIS among the first to realise its value. This doesn't mean, however, that it is only important to keep metadata about spatial datasets. It is important for any organisation to know exactly what datasets it holds and how to easily access them. Several documents have previously addressed the need for a metadatabase at the Environmental Research Institute of the Supervising Scientist, including reports by Devonport (1996) and Cawsey (1996). These reports recognise that development of a metadata database for an organisation should occur at a number of levels.

Information generated by the coastal management projects and the program itself will provide and utilise many different types and formats of data at a variety of levels. For example, at the 'highest' level, there will be project information providing descriptions of the projects involved in the Coastal Monitoring Program. Essentially, this degree of information will function as a project level form of metadata, or metadata pertaining to projects. Therefore information will include management and aims of the project, areas of responsibility, and the availability of funding and resources.

Information describing each dataset will form the next level in the information management system structure. This dataset level of metadata requires flexibility to allow for the high degree of variability exhibited by each dataset. Retaining a significant amount of flexibility, whilst maintaining a consistent approach to data management requires decision making about the level of metadata to collect. For example, a database describing many different runs of aerial photographs may be specified in two ways. Either the complete set of aerial photographs constitutes a single metadata record or each set of photos may be specified separately. Relationships between the project level and dataset level metadata should be maintained within the design of the information management system, as each project is composed of one or more datasets (fig 1). All documents produced as part of a project or used as references need to be collated and stored for future use. Documents can be related to a project, a dataset or both.

3.2 Management tools

The information management system is comprised of a structured framework for data and information management. This framework consists of various data management tools and forms the basis of the information management system. It constitutes a combination of hardware, software and other storage systems and archives. These systems require considerable resources for their development and implementation. The various components of the system should include a corporate database system, geographic information system (GIS), digital storage methods, physical storage methods and protocols for data management. However, not all components are complete at present.

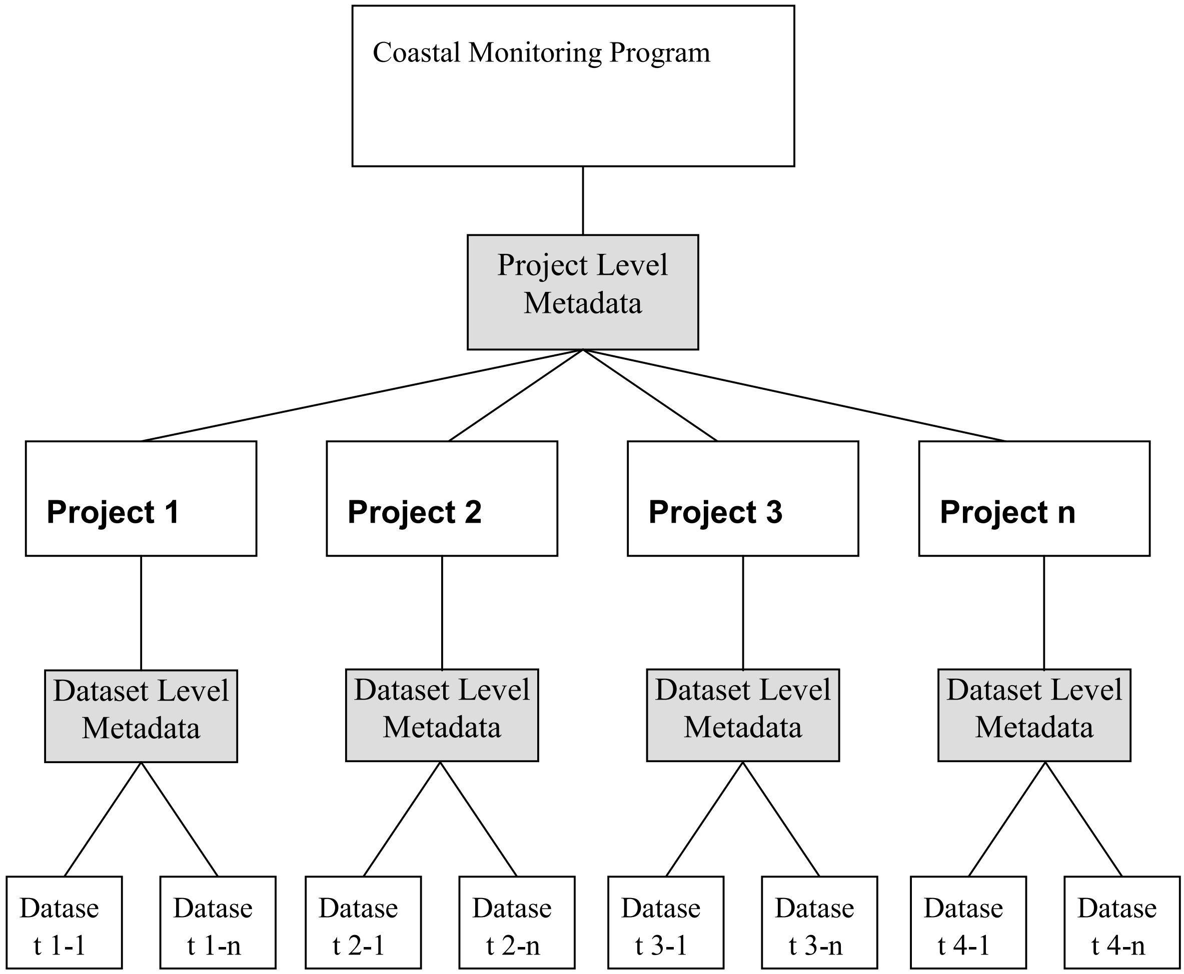

Figure 1 The three tiered approach to information management within the Coastal Monitoring Program

3.2.1 A corporate database system

A corporate database is required for data management in the Coastal Monitoring Program, and for other programs administered by the Environmental Research Institute of the Supervising Scientist. This would consist of a series of related databases including project information, personnel information (staff and external contracts), a data directory (metadatabase), a bibliographic database and links to actual data. Combined with the GIS, the database would suitably manage data for this and other Environmental Research Institute of the Supervising Scientist projects. Importantly the database must have a user-friendly front end to enable use by all staff. Staff must be consulted extensively during development for input and testing. Examples of similar databases exist within Environment Australia and other environmental research organisations. The suitability of these should be thoroughly investigated, as it may be possible to modify an existing database to suit the purpose.

The development of a comprehensive metadatabase forms an essential part of the corporate database system. Metadatabases can be directly obtained from other organisations, adapted from existing metadatabases, standard guidelines, or customised for a specific purpose. Metadatabases are available that have been developed within the ANZLIC guidelines based on spatial datasets. However, these databases are often inflexible and do not allow the inclusion of specific organisation oriented information. The development of a metadatabase for the Coastal Monitoring Program will need to be flexible and therefore require the development of a customised database. The dataset level metadatabase should be devised as a simple, user-friendly database to encourage all users to maintain accurate and recent metadata (Schweitzer 1998).

3.2.2 A Geographic Information System

The ability of GIS to collect, store, retrieve at will, transform and display spatial data from the real world makes GIS a powerful tool for environmental monitoring and management (Burrough & McDonnell 1998). Many projects included as part of the Coastal Monitoring Program involve production and analysis of spatial data through the use of dGPS technology and the analysis of remotely sensed imagery. A GIS is therefore required for the storage and analysis of these data, with the GIS operating as a specialised extension of the corporate database. Due to the specialised nature of spatial data management and analysis, the development of a GIS requires the installation of specific computer hardware and software as well as employment of skilled personnel to input data, perform analysis and data conversions and produce maps and other outputs. Hardware commonly associated with the development of a GIS includes the computer hard disk drive, network, CD ROM and other such media used for the storage of data and the running of GIS software. Other hardware includes digitisers and scanners, used for converting maps to digital form and printers, plotters and other display devices, used in the presentation of results (fig 2) (Maguire et al 1991). Software primarily refers to computer programs, disks or tapes containing these or other inter-changeable material for performing GIS operations. The use of various GIS software packages depends on functions being implemented, ie data input, storage, output and presentation, analysis and transformation (Burrough & McDonnell 1998). Today, major software packages have several hundred commands, which commonly incorporate a wide range of functionality. However, an important consideration in GIS software selection is the compatibility of the software with packages used within other environmental departments or organisation.

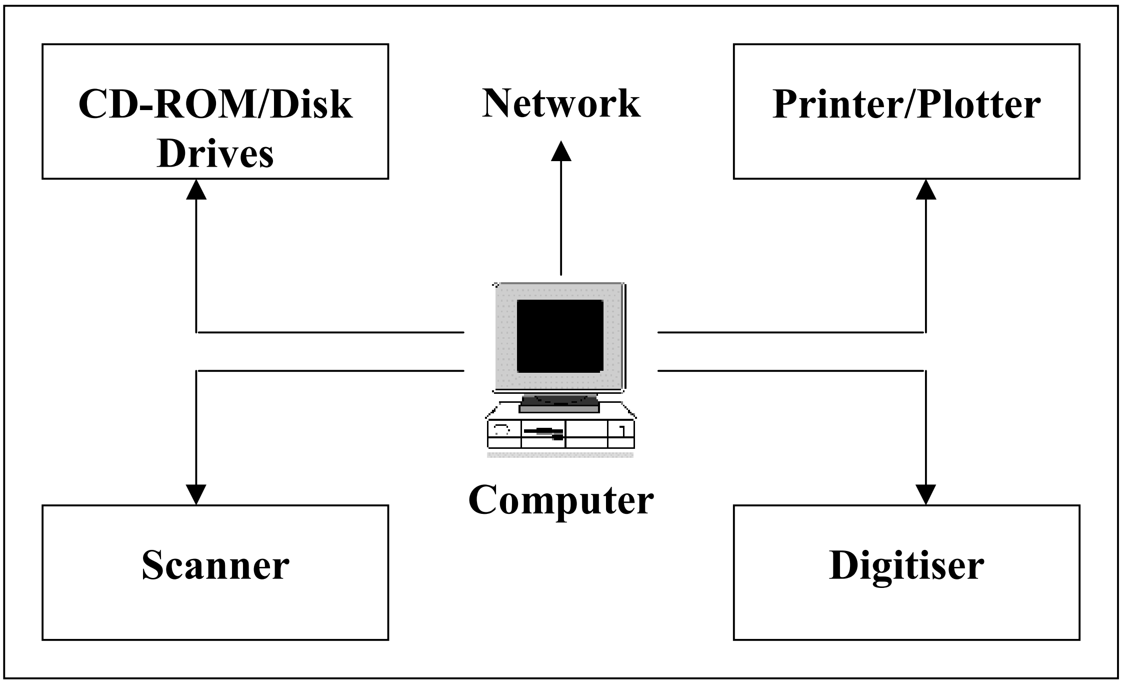

Figure 2 The major hardware components of GIS

3.2.3 Digital storage

The proliferation of computer generated information on the cultural and natural environment has resulted in the need to effectively store digital information (Goodchild 1993). The Coastal Monitoring Program has the potential to generate large amounts of digital data. Future hardware considerations for digital data storage need to be considered when developing an information management system. An adequate digital storage for all data to be stored on-line is required. This will be achieved by purchasing extra disk space. Additional hardware such as Personal Computers (PCs) or servers may also be required to interact with field equipment or handle large volumes of data. In particular, GIS and remotely sensed imagery have the potential to consume large amounts of disk space.

3.2.4 Physical storage

In addition to the virtual space of computer storage, the storage and registration of physical entities requires attention. Development of a physical storage methodology for the Coastal Monitoring Program will be heavily dependent on the nature of the data. For example, questions arise concerning storage of hard copy documents, aerial photographs and maps. Additionally, requirements to archive data to CD-ROM or other media, storage of media, and numbers of copies to be made also need consideration. It is likely that organisational guidelines covering some of these issues may be adapted to output from the Coastal Monitoring Program. The library of the Environmental Research Institute of the Supervising Scientist is the most appropriate and centralised place for physical storage systems.

3.2.5 Protocols for data management

In addition to systems for managing data, protocols should be developed to describe how different data types are handled. For example, it is necessary to ensure information is documented and stored correctly as it is acquired. Similarly, if a GIS coverage of survey points is downloaded from a dGPS, procedures must be established to ensure the information is retrievable for future use. Protocols for different types of data as well as a framework to support them are essential. The processes should be clear, with an explanation of procedures for data management included in the staff induction procedures.

3.3 Resources

Some consideration of resources, in terms of hardware and software needs, has been discussed in the previous section. However, personnel are needed to develop and implement metadata management systems. The GIS requires an operator/GIS manager. Other staff are required for the development of systems for digital and physical data storage. In addition, it is necessary that managers recognise information management is included in staff duties and staff appreciate the importance of information management. Many reasons exist for good data management, including recognition and accountability for information collected at public expense. Further, a commitment is required from all staff to ensure data management systems are developed and implemented at all levels.

4 Progress

Information sources and types have been identified and a considerable amount of information collected and collated. This includes historical and current datasets. For example, data collected on climate and hydrology is described elsewhere in this report. The basic systems and practices required for information management within the Coastal Monitoring Program have been described above. These systems could be extended and developed to assist with overall information management at the Environmental Research Institute of the Supervising Scientist. Further development and refinement will occur once systems are implemented and tested by the users.

4.1 GIS development

Data has been collected and processed by the Environmental Research Institute of the Supervising Scientist and Parks Australia North as a result of specific projects undertaken in the Region. The data includes satellite imagery, aerial photographs, firescar maps, administrative boundaries, drainage and hydrology, elevation data, vegetation, roads and mine sites.

The GIS data is stored in a logical file system and is backed up almost daily. The design of the GIS database organises data through consideration of the projection, datum and spatial extent of each dataset. The database is accessible via the Environmental Research Institute of the Supervising Scientist network and has been structured to provide an efficient and effective method of disseminating information to the end user. Satellite imagery is stored either on-line or on CD-ROMs. Metadata for the much of the dataset is already present in the Environment Australia Green Pages (http://www.environment.gov.au/database/edd/edd.html) and will also be entered into the local GIS metadatabase.

The GIS is now available for use by other staff in the Environmental Research Institute of the Supervising Scientist (Boggs et al 1999). This has been enabled by transfer of the GIS, including both data and software, to the Windows NT platform from the previously used unix platform. Several other positive effects include the integration of data storage systems for satellite imagery and GIS data between sections within the Environmental Research Institute of the Supervising Scientist. It also has reduced the cost of future software and hardware purchases.

4.2 Database development

Evaluation of various options for a spatial metadatabase has occurred. The Environment Australia Green Pages metadatabase has been tried and has been found to be unsuitable for direct use. This is due to inconsistencies and problems with the Internet link and the speed of operation. Also, the ANZLIC metadata tool has been evaluated. However, problems exist with the version currently distributed making it unsuitable for use. These problems include the inability to modify the database and problems within the database itself. For example, it is difficult to add extra fields to the database; there is a lack of integrity checks, and an inability to delete unwanted records.

The solution implemented within the Environmental Research Institute of the Supervising Scientist has been to develop a customised database based on existing metadata standards as part of the corporate system. This ensures system compatibility with the Environment Australia database. Data can be downloaded relatively easily into this database, whilst additional fields that relate to the Environmental Research Institute of the Supervising Scientist' internal data management can be added. Various controls have been incorporated in the database design including automatic checking for duplicate records and manipulation of basic functions. Development of the metadatabase in-house as part of a larger corporate database ensures that the databases are compatible and fully relational within the Institute.

Database development is proceeding in other areas. For example, a database of aerial photography has been instigated and populated with a large proportion of the sets of aerial photographs held at the Environmental Research Institute of the Supervising Scientist. This information includes the area covered by the photographs, the scale at which the data was captured, the storage location of the hard copies whether the photos have been scanned and, if so, the location of the digital image.

4.3 Document storage

Traditional and digital filing systems have been established for each of the coastal monitoring sub-projects. Registry files already exist for each sub-project. Documents relating to each of the projects are filed on the appropriate registry file. A digital directory structure with a directory for each of the smaller projects has been established. These areas are used to store documents and datasets relating to the projects.

4.4 Physical storage

The organisation and physical storage of aerial photography and topographic maps has been initiated. Aerial photographs have been collated and are stored in filing cabinets. These contain prints and flight diagrams for all photographs that have been entered in the database. This database contains information about all of the aerial photography held at the Environmental Research Institute of the Supervising Scientist and is updated as additioanal data sets are purchased or commissioned. Maps are stored in the library and are catalogued on both the library data base as well as a dedicated data base.

5 Conclusions

The design of an information management system for the Coastal Monitoring Program must be flexible and clearly structured to deal with the significant quantity and diversity of information generated by the program. In order to effectively design and implement an efficient information management system it is necessary to identify the information to be managed; describe the systems, practices and resources required to manage the information; and implement these systems over a period of time. The key to the design of a successful information management system is development and implementation of a comprehensive metadatabase for the program. A two tiered approach has been suggested for the management of metadata within the Coastal Monitoring Program. A customised metadatabase, based on the ANZLIC guidelines, has been developed for the Environmental Research Institute of the Supervising Scientist GIS database. This dataset level metadatabase can be adapted for use with other datasets associated with the program. It is of prime importance that a project level metadatabase is designed and implemented to provide a central, coordinating base for information management. Future progression of the information management project is dependent on resource availability, in particular for database development. Measures are being implemented to assist with data and information management. Outcomes are limited by the lack of a complete framework for data management. This best can be achieved through development of a comprehensive relational database.

While the coastal management program can make use of existing facilities to take care of the basic needs for project and dataset metadata, the information management requirements at the Environmental Research Institute of the Supervising Scientist need to be revisited. As a matter of priority progress should be made towards establishment of a corporate database. There needs to be a commitment to the establishment and maintenance of this database by all staff across the Institute. The process should be initiated by management in consultation with the Environmental Research Institute of the Supervising Scientist staff and other groups within Environment Australia. It needs to be stressed at all stages that the Environmental Research Institute of the Supervising Scientist should not be developing databases and in particular metadatabases in isolation from the rest of the Portfolio. The needs of other groups, including Parks Australia North, and the wider implications must be considered. Given that there is expertise within Environment Australia in this area it should be employed to best advantage. This approach would also strengthen existing links between the Environmental Research Institute of the Supervising Scientist and other sections of Environment Australia, a relationship which is of increasing importance in the present political environment.

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Chapter 3 Collation of baseline information: Regional processes

Environmental changes in the Alligator Rivers Region, as elsewhere in the wet-dry tropics, are driven by processes that are likely to cause switching of the floodplains between fresh and saltwater dominated ecosystems, reversing changes that have taken place in the past. These processes fall into two categories. First, large-scale atmospheric, hydrologic and oceanographic processes set the forcing conditions by providing the principal driving mechanisms for gross change at broad temporal and spatial scales. Second, at a local level these manifest as destabilisation of levees vegetated by mangroves along the coast and in the extensive estuarine reaches of the rivers. In turn, destruction of levees and subsequent modification of the geometry of river channels has potential effects on sedimentation processes and tidal hydraulics. Changes to the tidal regime may then favour headward extension of tidal creeks that may link to freshwater basins and ponds. The floodplain surface also changes independently of oceanographic and tidal processes, through natural changes related to the flood regime of its streams, sediment consolidation and settlement, evapotranspiration regimes and groundwater dynamics.

In the immediate context, the monitoring program is divided into two major components involving monitoring of:

1. Environmental change occurring at a regional scale and which directly affect the wet-dry tropics in general. These include atmospheric and hydrodynamic processes in van Diemen Gulf and the Alligator Rivers Region; and
2. Localised change in the environment related to processes that may occur throughout the Region but which act locally. Examples include the distribution and characterisation of wetland habitats and examination of biological and physico-chemical parameters as specific indicators of change.

Each suite of processes requires monitoring and analysis to determine its relative contribution to contemporary environmental change on the floodplains and along the coast. Subsequently, a full system analysis and modelling of environmental change is proposed and will be developed over time.

Given the spatial and temporal nature of the monitoring, automatic recording and sampling equipment is used wherever practicable and the data collated within the Geographic Information Systems technology. Agencies with existing skills and equipment have been encouraged to collaborate in the monitoring program, thereby potentially minimising the expenditure and maximising the potential for generic use of the information. This is apparent in the collation of the historical information comprising much of this section of the report.

3.1 Environmental change at a regional scale

Several of the projects examining regional-scale processes will establish the context for assessment of environmental change on the floodplains. These have had the highest priority for implementation, although they remain substantively incomplete. They include reports on the current status of monitoring of atmospheric, oceanographic, and hydrologic conditions as well as a review of land use change in the Alligator Rivers Region.

Four papers are included in this section of the publication.

Climatological changes occurring from season to season, as well as at interannual and longer time scales, determine the intensity of geomorphologic processes and affect the distribution of vegetation in the coastal environment. The natural variability of climate necessarily is established from meteorological records. Hence Michael Saynor, Dave Walden, Raymond Hall and Bruce Ryan examined availability of climatic data in their paper 'Climate record for the Alligator Rivers Region' as a basis for the assessment and monitoring of a suite of biophysical processes including hydrological patterns, vegetation distribution and oceanographic conditions (Paper 3).

The theme of data availability was further developed by Dave Walden in his paper 'Surface hydrology of the Alligator Rivers Region' (Paper 5), in which he summarises the availability of information from stream gauging stations throughout the Region. The paper emphasises the lack of long-term measurement and Walden points out that an assessment of monitoring requirements should be made as part of a strategic evaluation of future hydrological modelling requirements.

In their paper on the 'Climatology and physical oceanography of van Diemen Gulf: Preliminary acquisition of baseline information' (Paper 4), Ian Eliot, Matthew Eliot and Michael Saynor describe progress made in a several sub-projects. These include examination of seasonal and interannual variation in wind direction and velocity, the tidal regime of van Diemen Gulf, sea level change, bathymetric mapping, description of water circulation, the impact of ENSO events and shoreline change. The projects they report are ongoing so that detailed results are not available.

The environmental changes identified in the regional projects all influence potential land use in the Region. Similarly, environmental change initiated by a particular land use may influence future land management strategies in the Region under consideration. Hence a 'History of land use and resultant environmental change in the Alligator Rivers Region' (Paper 6) has been compiled by Abbie Spiers to provide a baseline from which future change may be assessed. Her records demonstrate the dynamism of the Region and indicate the ecological costs accruing from changing land use.

Paper 3 Climate record for the Alligator Rivers Region

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Abstract

The climate record for the Alligator Rivers Region is being investigated as part of a program for assessment and monitoring of coastal change for the Region. The program has been initiated by the Environmental Research Institute of the Supervising Scientist at Jabiru in the Northern Territory of Australia. Review of the climate information collected in the Region has been undertaken to provide a baseline of information for the assessment and monitoring of a suite of biophysical processes, including hydrological patterns, vegetation distribution and oceanographic conditions.

Weather stations that have been deployed throughout the Alligator Rivers Region since 1910 have been identified and the climate coverage has been considered. It is apparent that the coverage is intermittent, concentrated around settled areas, or those subject to mining development. Such coverage provides only an indication of the climate influencing the wider area of the Alligator Rivers Region. Consequently, it is recommended that additional weather stations should be established. The location of these stations should be strategically chosen, to integrate with system modelling and climate analysis, currently under development.

Key words: Alligator Rivers Region, Kakadu National Park, weather stations, climate records

1 Introduction

The Alligator Rivers Region (fig 1) is a vast, sparsely populated area with immense natural and cultural significance, some 150 km east of Darwin, in the Northern Territory of Australia (Finlayson & von Oertzen 1996). The name of the Region is derived from its rivers and encompasses the 20 000 km^2 of Kakadu National Park. A significant area of the Alligator Rivers Region is low relief plains, river floodplains, wetlands and deltaic floodplains (Woodroffe et al 1986, Wasson 1992) with the majority of the drainage into van Diemen Gulf via the major river systems. Low elevation throughout the Region makes it extremely susceptible to variations in ocean water levels.

Vulnerability of the Alligator Rivers Region to climate change was identified by Bayliss et al (1997). In view of the susceptibility of the Alligator Rivers Region to environmental change, Bayliss et al (1997) made recommendation for development of a program to assess and monitor coastal change in the Region. The recommendation has been implemented and development of the program is being coordinated by the Environmental Research Institute of the Supervising Scientist. Investigation of the climate record of the Alligator Rivers Region and analysis of the available climate monitoring network are being undertaken as a sub-component for the broader coastal assessment and monitoring program.

Alligator Rivers Region

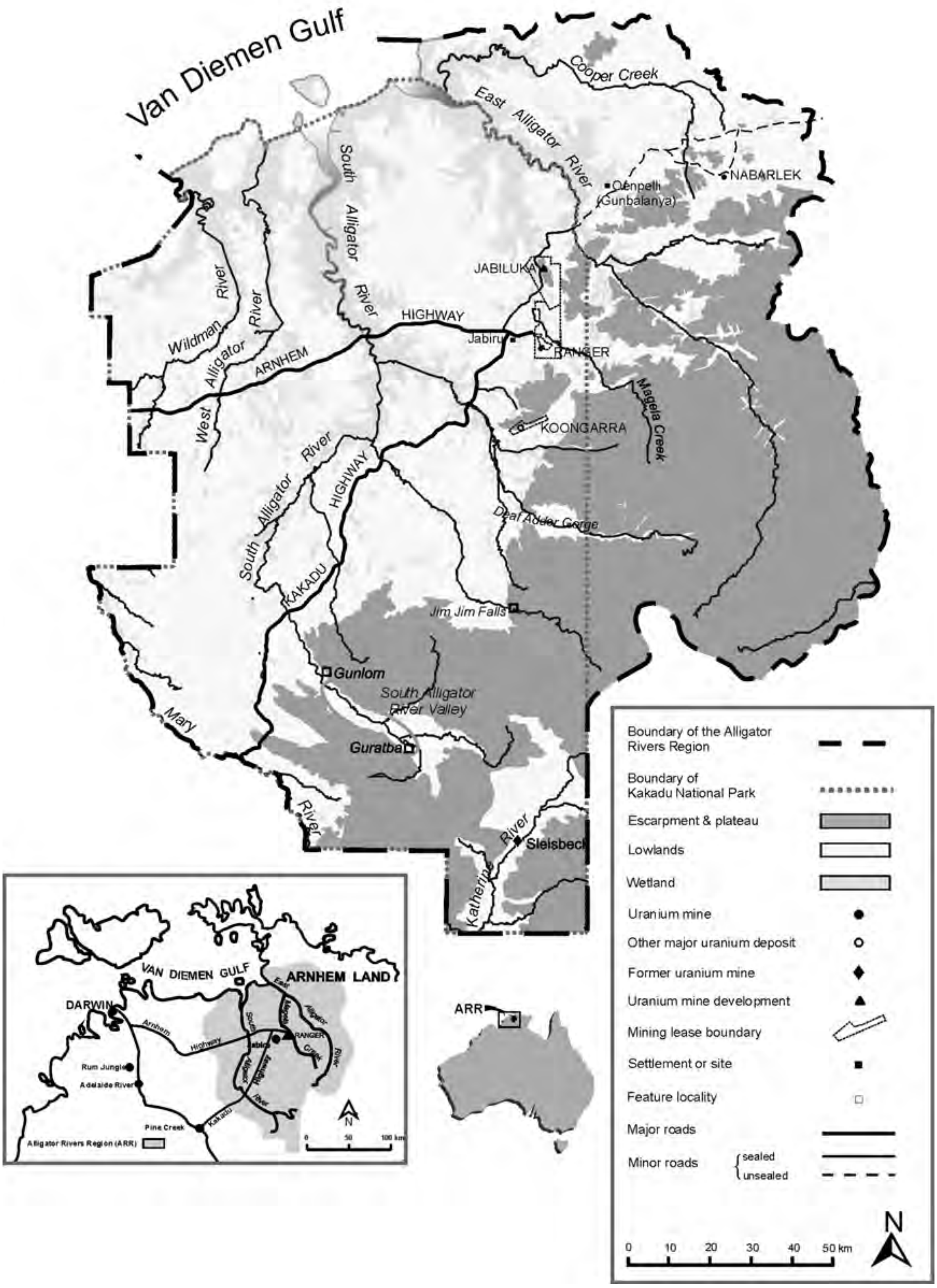

Figure1 Location of the Alligator Rivers Region

As part of the broader program, climate records are required for analysis and modelling of the behaviour of:

- van Diemen Gulf oceanography;
- stream and wetland hydrology;
- vegetation distributions.

A different suite of climatic parameters affects each of these components, over different temporal and spatial scales. Historic variability of climate, land-use, morphology and vegetation provides a baseline from which future variability may be assessed. The historical record of recent climate change and its biophysical effects are at least as significant as the broad picture of environmental change afforded by investigation of Holocene landform evolution (Bayliss et al 1997).

2 Aim and objectives

The aims of this paper are to:

- determine existing baseline climate information for the Alligator Rivers Region;
- determine present climate monitoring coverage of the Alligator Rivers Region;
- establish if the information is sufficient to provide a regional coverage.

Objectives reached to achieve these aims are to:

- identify agencies responsible for recording of historic climate data sets;
- identify and list previous climate analyses;
- collate metadata regarding climate data sets, particularly location and deployment with respect to each climate parameter;
- assess the capacity for the historic climate data sets to provide coverage across the Alligator Rivers Region.

3 Background

Climate records in the Alligator Rivers Region and neighbouring regions are relatively limited. Following common practice, weather stations have typically been associated with human habitations and consequently the monitoring sites have records limited by the relatively short history of townships in the region. For example, Jabiru has a climate record extending back to 1982. Within the region, the longest climate record is approximately 80 years, from Gunbalunya (Oenpelli). Longer-term climate records are available for Darwin.

Climate conditions have been described by a range of authors, including the Australian Bureau of Meteorology (1961), McAlpine (1969), Christian and Aldrick (1977), Hegerl et al (1979), Woodroffe et al (1986), Nanson et al (1990), Riley (1991), Wasson (1992), Butterworth (1995), Russell-Smith et al (1995), McQuade et al (1996) and Bureau of Meteorology (1999). On the basis of these authors' works a general description of the climate can be made.

The climate of the Alligator Rivers Region is defined as wet-dry tropical with a Wet season duration of 4.5 to 7 months (Nanson et al 1990). Ninety-two percent of the average rainfall falls between November and March (McQuade et al 1996). Mean annual rainfall ranges from approximately 1300 mm in the south to 1500 mm at Jabiru, and humidity is highest from

January to March (Russell-Smith et al 1995). At Jabiru, temperatures are high throughout the year, with a lowest mean daily maximum of 31.3ºC in June and a highest of 37.5ºC in October (McQuade et al 1996).

The Wet season is marked by monsoonal depressions bringing heavy rain and occasional tropical cyclones (Russell-Smith et al 1995). Cyclones produce torrential rain, destructive winds, flooding and occasionally severe coastal storm surges. For the 60 year period ending in 1975, at least nine cyclones passed over the Alligator Rivers Region, with another eleven passing sufficiently close to cause strong winds and rain (Hegerl et al 1979). The Dry season has cooler temperatures and extends from May to September, with little or no rain falling, even on the coast (Wasson 1992). Annual potential evaporation exceeds rainfall in most years, ranging from 2400–2700 mm per year (Russell-Smith et al 1995). Between April and September, the winds are predominantly from the south-east and east. From November to February, the winds are more variable, and often have a strong westerly and northerly component.

4 Methods

4.1 Oceanography of van Diemen Gulf

Critical parameters affecting the oceanography of van Diemen Gulf include cyclone distribution (intensity, frequency and path), wind distribution (speed and direction, with spatial variation), pressure distribution and wave activity.

The primary source of suitable information is from the Australian Bureau of Meteorology (BOM). Data sources available include:

- Australian cyclone database, detailing all cyclone parameters observed by the BoM
- weather stations surrounding van Diemen Gulf, measuring wind speed and pressure
- Australian regional wave hindcasting.

Personnel from the University of Wollongong are presently undertaking variability analysis of wind conditions across van Diemen Gulf (Clarke pers comm 1998). Selection of weather stations from which to examine variability has been on the basis of record length, completeness and coverage across the Gulf.

4.2 Stream and wetland hydrology

Climate parameters required for hydrological modelling depend upon the type and detail of modelling to be undertaken. Basic water balance modelling requires, as a minimum, rainfall records, and evaporation. Water quality modelling may additionally require solar radiation, temperature and humidity measurements. The area to be covered by the network of climate measurements should extend beyond the extremities of the Alligator Rivers Region catchment area.

Spatial distribution required for each of the climate parameters is dependent upon the hydrological modelling scale and the spatial variability inherent in the climate variable. For example, the most appropriate rain gauge network has a similar density to the number of sub-catchments to be modelled.

Climate information suitable for hydrological modelling is available from various government authorities and private companies that have operated within the Alligator Rivers Region or near to the region. Government agencies contacted with regard to climate data were:

- Australian Bureau of Meteorology
- Northern Territory Department of Lands, Planning and Environment
- Parks Australia North.

Mining companies that have operated within the Alligator Rivers Region have, at the minimum, collected rainfall records, to assist with water management. Mining companies contacted to provide information regarding climate records were:

- Energy Resources of Australia (ERA), at Ranger uranium mine
- Queensland Mines Limited (QML), at Nabarlek.

From each organisation contacted, metadata requested for each of the stations included: location, length of record, instrumentation, data storage and download mechanism.

Metadata for the climate stations is detailed in this paper.

4.3 Vegetation distributions

Climate parameters influential for vegetation distributions include rainfall, temperature, evaporation, solar radiation, humidity and soil temperature. Sources of climate information suitable for vegetation distribution analysis are identical to those required for stream and wetland hydrological modelling, and have been detailed within this paper.

Spatial variability inherent in vegetation distribution is strongly linked to local topographic and hydrologic effects. In addition, seasonal variation is believed to be stronger than interannual variation. Only long-term trends in climate variation may be examined, over which time-scale, social and biophysical change must be considered. Hence, analysis of vegetation distributions with respect to climate variables can, at best, be undertaken on a coarse scale, in both space and time.

5 Weather stations in the Alligator Rivers Region

Rainfall data is the most common climatic parameter collected in the Alligator Rivers Region. Rainfall stations located within the Region are listed in table 1 which also lists the custodian of the information. At some stations further instrumentation is installed to measure additional climate parameters. In particular, the Australian Bureau of Meteorology typically installs two forms of weather station, measuring climatic parameters as detailed below:

Automatic Weather Station (AWS)

Temperature, wind speed, wind direction, pressure, rainfall, humidity (by sensor)

Synoptic Weather Station (SWS)

Temperature, wind speed, wind direction, rainfall. Some later stations may also measure pressure.

The Environmental Research Institute of the Supervising Scientist has installed five fully automated weather stations in the Alligator Rivers Region. These stations can collect the following parameters — air temperature, soil temperature, soil moisture, barometric pressure, humidity, rainfall, wind speed, wind direction and solar radiation. Probes and sensors have been installed to Australian Bureau of Meteorology standards in a Stevenson screen. ERA Ranger Uranium Mine also collects climate data in addition to rainfall.

Table 1 Rainfall stations located in the Alligator Rivers Region

Site	Number	Start	End
Bureau of Meteorology			
Jabiru Airport	014198	1971	1990
Jabiru Airport AWS	014198	1995	present
Jabiru Town	014208	1983	present
Gunbalunya (Oenpelli)	014042	1910	present
South Alligator	014284	1995	present
Cooinda	014256	1991	1996
Border Store	014271	No Data	
Mount Borradaille	014286	No Data	
Environmental Research Institute of the Supervising Scientist			
Jabiru East		July 1997	present
Nabarlek		Nov 1995	present
Djarr Djarr		Oct 1997	present
East Alligator		Nov 1997	present
Mudginberri		Nov 1999	present
Swift Creek		Dec 1998	present
Upper Main (Swift Creek)		Dec 1998	present
East Tributary (Swift Creek)		Dec 1998	present
ERA Ranger Mine			
Jabiluka		Aug 1994	present
Jabiru Airstrip		Jan 1971	present
Ja Ja (Djarr Djarr)		1978	1991
Tailings Dam		Mar 1991	present
Ore Body No. 3		Mar 1991	present
Queensland Mines Limited			
Nabarlek	Station 1	Jan 1979	Oct 1995
Nabarlek	Station 2	Sep 1981	June 1995

A list of weather stations and the climatic parameters collected at each is provided in table 2.

Table 2 Weather stations located in the Alligator Rivers Region, collecting parameters other than rainfall

Site	Number	Start	End	Parameters
Bureau of Meteorology				
Jabiru Airport AWS	014198	1995	present	Temperature, wind, pressure, rainfall, humidity
South Alligator	014284	Unknown		Evaporation
Environmental Research Institute of the Supervising Scientist				
Jabiru East		July 1997	present	Air and soil temperature, soil moisture, barometric pressure, humidity, rainfall, wind direction and speed at 2 m and 10 m and solar radiation
Nabarlek		Nov 1997	present	Air and soil temperature, soil moisture, barometric pressure, humidity, rainfall, wind direction and speed at 2 m and 10 m and solar radiation
Djarr Djarr		Oct 1997	present	Air and soil temperature, barometric pressure, humidity, rainfall, wind direction and speed at 2 m and 10 m and solar radiation
East Alligator		Nov 1997	present	Air and soil temperature, barometric pressure, humidity, rainfall, wind direction and speed at 2 m and 10 m and solar radiation
Mudginberri		Nov 1999	present	Air and soil temperature, barometric pressure, humidity, rainfall, wind direction and speed at 2 m and 10 m and solar radiation
ERA Ranger Mine				
Jabiluka		Aug 1994	present	Temperature, relative humidity, pressure wind speed and direction
Jabiru Airstrip	Monitored	Jan 1994	present	Temperature, relative humidity, pressure wind speed and direction, solar radiation
	Starlog station	Dec 1988	Nov 93	Temperature, relative humidity, wind speed and direction
	Manual Observations	Nov 1977	Jun 1990	Temperature, relative humidity, wind speed and direction
	Manual Observations	Nov 1971	present	Evaporation

6 Weather stations in close proximity to the Alligator Rivers Region

The broad scale nature of climate systems determines that weather stations collecting data in areas adjacent to the Alligator Rivers Region may provide valuable information for the analysis of system change within the Region. Due to the wide spread coverage, Australian Bureau of Meteorology weather stations have been examined. Stations collecting rainfall adjacent to the Alligator Rivers Region are listed in table 3, while stations collecting other weather parameters are listed in table 4.

Table 3 Rainfall stations located adjacent to the Alligator Rivers Region

Site	Number	Start	End
Bureau of Meteorology			
Cape Don	014008	1917	1990
Cape Don AWS	014245	1994	present
Black Point	014153	1965	present
Seven Spirit Bay	014249	1991	1996
Minjilang	014011	1947	present
McCluer Island AWS	014274	1994	present
Murganella	014180	1966	1996
Warruwi	014401	1916	present
Carmor Plains	014281	1993	present
Point Stuart AWS	014254	1994	present
Wildman River	014275	1993	present
Marrakai	014278	1993	present
Mount Bundy	014283	1995	1996

Table 4 Bureau of Meteorology weather stations located adjacent to the Alligator Rivers Region, collecting parameters other than rainfall

Site	Number	Start	End	Parameters
Cape Don AWS	014245	1994	present	Temperature, wind, pressure, rainfall, humidity
Cape Don	014008	1946	1991	Synoptic station
McClure Island AWS	014274	1994	present	Temperature, wind, pressure, rainfall, humidity Synoptic station
Point Stuart AWS	014254	1994	present	Temperature, wind, pressure, rainfall, humidity Synoptic station
Black Point	014153	1991	present	Synoptic station
Minjilang	014011	1968	1991	Synoptic station
Warruwi	014401	1966	present	Synoptic station
Mount Bundy	014283	1995	1996	Evaporation

7 Conclusions and recommendations

The prime outcome of this paper is the identification of climatic information for the Alligator Rivers Region and adjacent areas. Within the Alligator Rivers Region, rainfall stations are located at small settlements, at Jabiru and the mining facilities. More sophisticated stations are located at Jabiru or at the mining facilities. There is climate information available adjacent to the Alligator Rivers Region either from settlements in Arnhem Land, or stations to the west.

Climate coverage of the Alligator Rivers Region is intermittent, due to its restriction to settled and mined locations. Information is sufficient only to give an indication of the climate that influences the whole of the Alligator Rivers Region. There are large areas devoid of climatic information and adequate modelling or climate analysis will require establishment of new weather stations. However, determination of the station density requires greater development of the system modelling and climate analysis programs. Such information is ultimately of importance for detection and understanding of long-term (decadal) environmental change and its implications for effective management of the Region.

Recommendations for further progress include:

1. Define the location, type and scale of hydrological modelling and vegetation analysis anticipated to be undertaken for the Alligator Rivers Region. This will determine if the existing climate network is sufficient to allow meaningful interpolation over the area of interest.
2. Identify locations of interest, which have poor coverage from the existing system, so as to improve coverage of the climate network.
3. Prioritise any new weather stations, to ensure establishment costs are constrained.
4. Establish the nominated weather stations.

It is possible that the preferred climate measuring system will consist of two or more networks of instrumentation. Slowly varying parameters such as barometric pressure or solar radiation may be measured on a coarse network. More rapidly varying parameters, such as rainfall, should be measured on a relatively fine network.

8 Acknowledgments

The authors would like to thank those who provided information:

- J Grinstead, S Cleland and R Christmas from the Australian Bureau of Meteorology;
- D Kinter from the Water Resources Division of the NT Department of Lands, Planning and Environment;
- T Spedding from Energy Resources of Australia Ltd — Ranger uranium mine;
- A Wellings, P Shaunessy, L Curtis, S Winderlich and G Spiers, District Supervisors from Parks Australia North.

For preparation of the diagrams, the authors also wish to thank B Bayliss (Environmental Research Institute of the Supervising Scientist).

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Paper 4 Climatology and physical oceanography of van Diemen Gulf: Preliminary acquisition of baseline information

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Abstract

Oceanographic investigations of van Diemen Gulf are being undertaken as a component of the Alligator Rivers Region Coastal Monitoring Program initiated by the Environmental Research Institute of the Supervising Scientist at Jabiru, in the Northern Territory of Australia. The monitoring program is intended to provide baseline information of direct relevance to management of the Alligator Rivers Region, but also may be relevant to management of all coastal plains bordering the Gulf.

Oceanographic processes interact with river discharge, basin structure and sediment availability to determine the mode and extent of floodplain development. Hence, the primary aims of this component of the Coastal Monitoring Program are to determine the natural variability of prevailing atmospheric and oceanographic processes operating in van Diemen Gulf and ascertain their affect on its waters and coastal margins. Particular attention will be given to the effects of onshore wind activity and fluctuations in sea level on the coastal margin of Kakadu National Park. Subsidiary objectives required to achieve the aim relate to use of information gathered in the monitoring process. These will be met through implementation of a suite of sub-projects:

- Examination of short-term variation in local wind direction and velocity around van Diemen Gulf;
- Establishment of several tide stations to enable regional change in water levels to be determined;
- Determination of characteristic patterns of spatial and temporal variation in sea level around the shores of van Diemen Gulf in response to seasonal, interannual and other short-term variations in climate;
- Description of water circulation and identification of any relationship between ENSO events;
- Water-circulation and sea level fluctuation;
- Detailed hydrographic survey of the basin;
- Identification of sediment movement, particularly near the shore.

Some of the sub-projects have commenced and progress is reported here. Others, such as the hydrographic surveying and determination of water circulation patterns, are dependent on the development of collaborative research partnerships with other agencies as well as availability of resources. Regardless of the state of progress, recommendations have been made for further implementation of the overall program.

Key words: Alligator Rivers Region, van Diemen Gulf, coastal monitoring, oceanography, climatology

1 Introduction

Since little is known about climatologic and oceanographic processes operating in van Diemen Gulf an atmospheric and oceanographic monitoring framework is currently being designed and established in the Region. Examination of the oceanographic process for van Diemen Gulf is recognised as an important component of the Alligator Rivers Region Coastal Monitoring Program (Eliot et al 1999) being established at the Environmental Research Institute of the Supervising Scientist.

Acquisition of baseline information will then be useful in determining the effects of short-term variation in climate and fluctuation in sea level have on the water and sediment circulation, shorelines and wetlands in and surrounding the Gulf. It will provide a context for management of the resources of Kakadu National Park adjoining lands as well as the infrastructure used to access them. In turn, it may be used to identify likely changes due to predicted changes in climate and sea level.

Van Diemen Gulf is a large, almost fully-enclosed body of water located approximately 50 km east of Darwin in the Wet-Dry tropics of the Northern Territory (fig 1). It is bounded in the south by lands bordering the Adelaide and Mary Rivers as well as the coastal margin of the Alligator Rivers Region. Melville and Bathurst Islands bound it to the north and west and Cobourg Penisula to the north and east. Several large rivers debouch into the Gulf along its southern coastline. These include the Adelaide, Mary and Wildman, as well as the South Alligator, East Alligator and West Alligator Rivers (fig 1).

Kakadu National Park is situated on the south-eastern shoreline of the Gulf, in the Alligator Rivers Region. The Park is an area of immense heritage value and is listed as a World Heritage site for both cultural and natural values. Its extensive coastal wetlands are also listed as internationally important under the Ramsar Convention (Finlayson & von Oertzen 1996). Interactions between oceanographic processes in the Gulf and the fluvial processes on the coastal plains directly affect the biological status of the Park and its landform development. Hence, a thorough appreciation of them is germaine to effective, long-term management of the Park, as it is to management of wetlands elsewhere in the wet-dry tropics.

At present it is not fully known how important coastal margins and freshwater meadows respond to natural variation in climate, quite apart from their potential responses to predicted climate change and sea level rise (Bayliss et al 1997). Environmental responses to climate and sea level changes are manifested through hydrological, hydrodynamic, geomorphological and ecological processes. The importance of tidal and sea level fluctuation has been acknowledged and examined for some fluvial systems along the southern coastline (Woodroffe 1988, Woodroffe & Mulrennan 1993). Development of the coastal plains along shorelines of the Gulf 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 (Chappell 1988, Woodroffe & Mulrennan 1993). Hence, an understanding of the coastal hydrodynamics of the Gulf, 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 on the coastal margins.

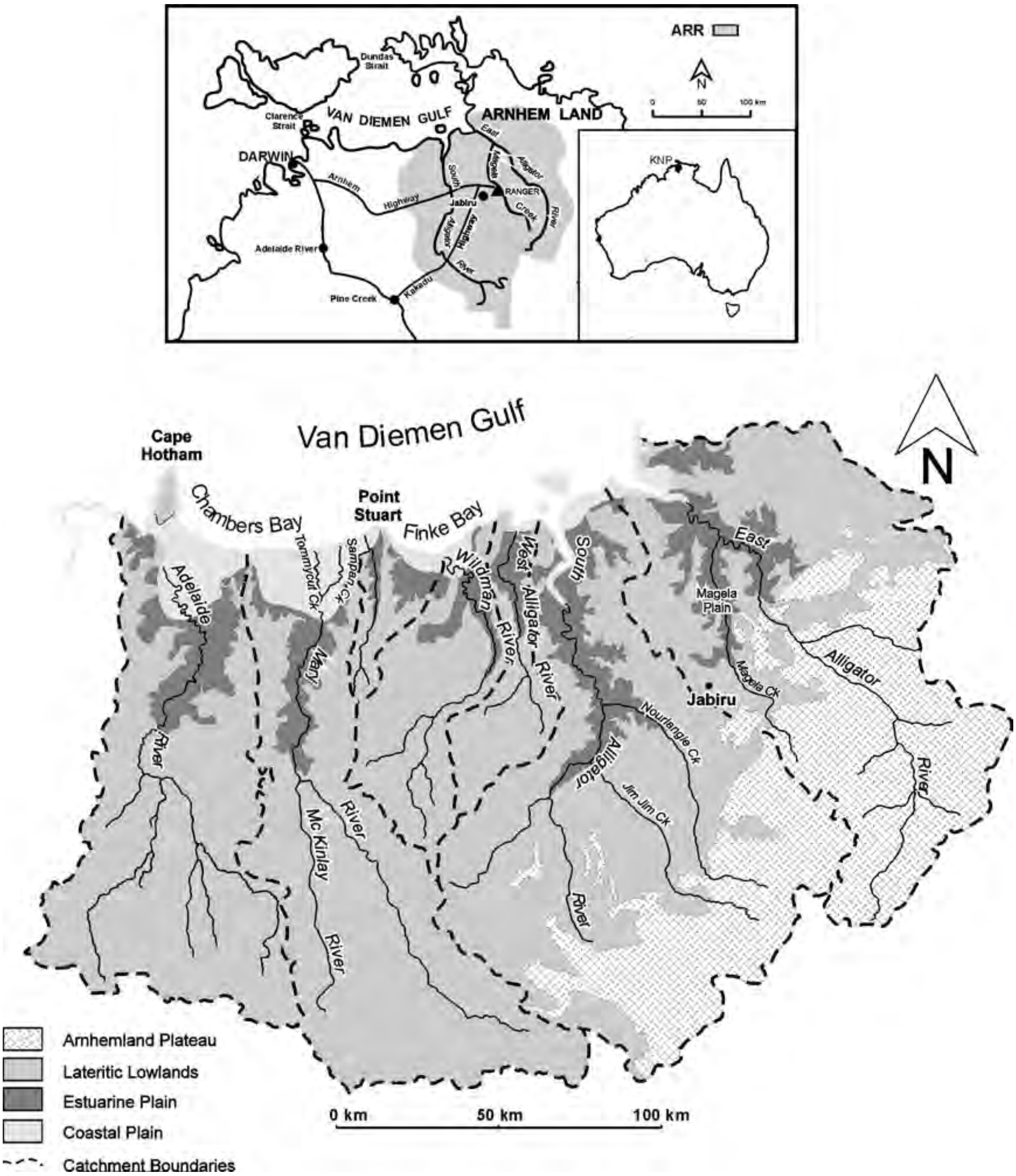

Figure1 Location diagram for van Diemen Gulf and the Alligator Rivers Region

There is a very substantial body of information describing geologic and, particularly, recent historical changes to the coast and lands of the lower Mary River and parts of the Alligator Rivers Region (Chappell 1988, Knighton et al 1991, 1992, Woodroffe & Mulrennan 1993, Wasson 1992). Oceanographic processes contribute to many of these changes but are not as thoroughly described. However, they are manifested by very high rates of shoreline erosion, changing tidal regimes within the river systems, and contribution to salt water intrusion into freshwater ecosystems. Changes resulting from these processes are seen in reduction of the fringing mangroves along the shores of the Gulf, expansion of the samphire and saltflat areas, colonisation of mangroves along estuarine levee banks, and the headward erosion of tidal creeks. The processes of change are interactive with those of the river systems and with human interference, particularly the introduction of feral animals and infestation of introduced plants. While the terrestrial and riverine processes of change are reasonably well researched remarkably little is known of the hydrodynamic processes in van Diemen Gulf and their immediate impacts on the shorelines and estuaries of the Alligator Rivers Region.

2 Project aims and objectives

2.1 Aims

The primary aims of this component of the Alligator Rivers Region Coastal Monitoring Program are to determine the natural variability of prevailing atmospheric and oceanographic processes operating within van Diemen Gulf and assess their impact on the waters and coastal margins of the Gulf. Particular attention will be given to the effects of onshore wind activity and fluctuations in sea level on the coastal margin of Kakadu National Park in the Alligator Rivers Region.

2.2 Objectives

Subsidiary objectives to achieve the aim relate to use of information gathered in the monitoring process for:

- establishment of short-term variation in local wind direction and velocity;
- determination of relationships between weather conditions, sea level fluctuation, water circulation and shoreline changes on the coast of the Alligator Rivers Region;
- measurement and description of tides in the east Alligator Rivers Region the Gulf;
- determination of sea level variation in relation to barometric, wind and wave effects;
- numerical modelling of water circulation in the Gulf;
- examination of relationships between sea level fluctuation and tidal water movement in the Wildman, South Alligator and East Alligator Rivers during low-flow conditions;
- examination of the relationship between ENSO events, water circulation and sea level fluctuation in the Gulf.

3 Van Diemen Gulf

Van Diemen Gulf is approximately 135 km long E-W, from the East Alligator River to Cape Hotham, and 75 km wide N-S from Burford Island to Point Stewart (fig 1). Water depths in Clarence Strait, the western entrance to van Diemen Gulf, vary up to approximately 50 m but are generally less than 20 m. Islands, reefs and shoals are plentiful. In the strait they have a marked east-west orientation consistent with strong water flow in and out of the Gulf basin. The shoals change orientation inside the basin, varying through a southwest to northeast orientation offshore from Melville Island to a more north-south trend near Dundas Strait at the northern entrance to the Gulf. A broad shallow shelf extends along the southern and eastern shores of the Gulf. Its seaward margin, linked to submarine deltaic morphology, is irregular in plan form and approximately 18 km offshore. In section, the shelf slopes seaward to approximately 10 m depth. The floor of the Gulf basin is irregular, with numerous reefs and shoals. Depths range up to 100 m but are generally less than 30 m in the main body of the basin. They increase to over 100 m in Dundas Strait, between Melville Island and Cobourg Peninsula. The geometry of the basin is of significance for the range and complexity of oceanographic processes it potentially experiences.

Photogrammetric and field observations of saltwater intrusion of freshwater wetlands on the low-lying coastal plains of van Diemen Gulf have been reported by Chappell (1988), Knighton et al (1991, 1992), Woodroffe and Mulrennan (1993) and Cobb (1997). Their observations indicate that saltwater incursion of freshwater wetlands currently is occurring in two morphologically dissimilar circumstances. First, tidal creeks are extending directly landwards from the shoreline in Chambers Bay, with Tommycut and Sampan Creeks extending inland across the coastal wetlands of the Mary River. Second, similar extension of tidal creeks has occurred in the estuarine reaches of major established streams in the Alligator Rivers Region. In both environments the rate of extension is greatest near the coast where the interaction of tide and storm surge with flood discharge is greatest. It indicates that the role of oceanographic processes should not be discounted in any consideration of factors contributing to saltwater intrusion of the floodplains.

Further, Woodroffe et al (1986) and Chappell (1988) have pointed out that changes in tidal amplitude throughout the rivers of northern Australia may be linked with expansion of the networks of tidal creeks. The elevation of spring tide water level will increase in the estuarine reaches of a river if meander cut-off or shallows through shoal formation shorten it (Chappell 1988). In both contexts changes in the extent of tidal creeks are viewed as changes in river morphology that occur over hundreds to thousands of years. The response to broad geomorphic change, extension of the tidal creeks and salinisation of floodplain basins, then occurs very rapidly. This is indicated by current rates of tidal creek extension into the floodplains bordering the southern shores of van Diemen Gulf.

Descriptions of summer-wet versus winter-dry conditions in the Alligator Rivers Region identify the main climatological features of northern Australia as being related to the presence of a monsoonal trough in summer and its absence in winter. This results in a reversal of winds from approximately WNW to SE from summer to winter (McQuade et al 1996). It implies that water is likely to be pushed into van Diemen Gulf to raise average water levels in summer, when the onshore WNW winds are most frequent. Conversely, the SE trades prevalent in winter are offshore. They are likely to drive water from the Gulf, thereby lowering average sea level in the Dry season. Barometric effects on sea level and seasonal variation in the wave regime further complicate these effects.

Seasonal variations are not constant from year to year. However, the extent of annual variation occurring remains open to question. Hence the proposition that the duration of the reversals and the frequency of winds from a particular direction are likely to vary interannually was examined by comparing the monthly wind frequencies for ENSO and Anti-ENSO years. The results are illustrated in figures 2 and 3 respectively, and in table 1, where it is clear that there is considerable interannual variation. Further investigation of the variability is warranted.

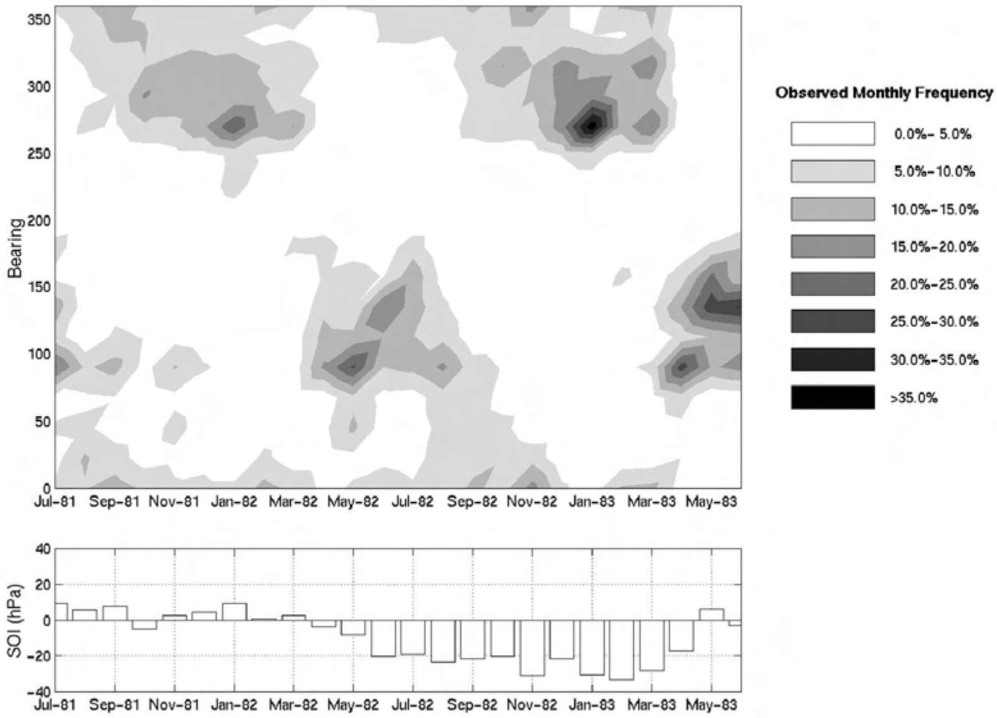

Figure 2 Monthly wind direction frequency for an ENSO period

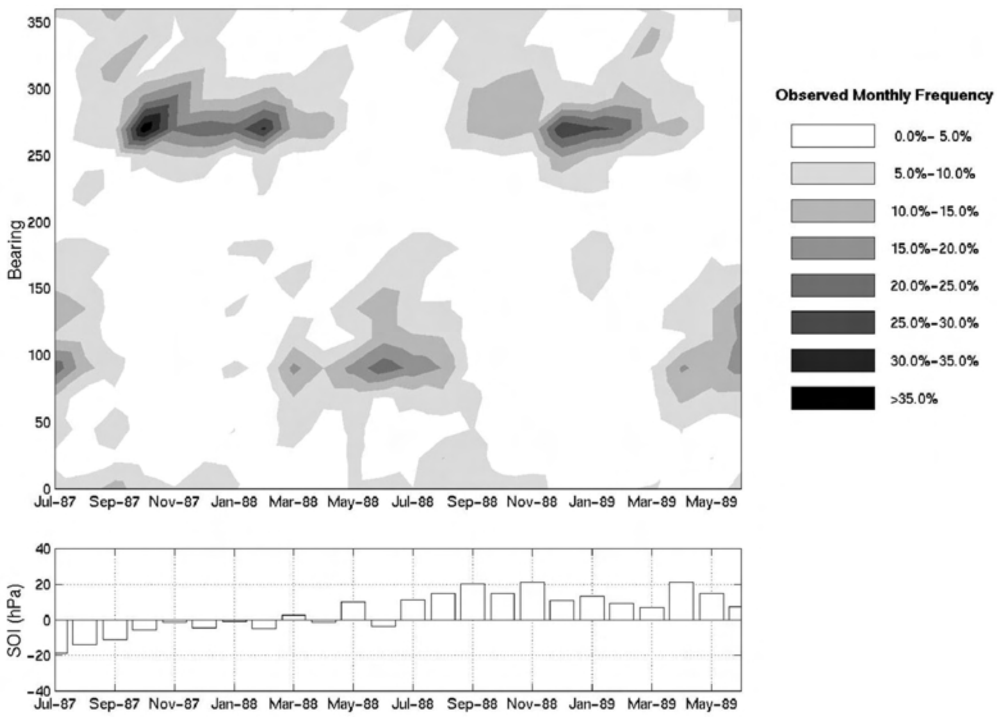

Figure 3 Monthly wind direction frequency for an ANTI-ENSO period

Table 1 Seasonal variations and wind patterns for van Diemen Gulf

		ENSO	Anti-ENSO	Summer 81/82	Winter 82	Summer 82/83	Summer 87/88	Winter 88	Summer 88/89
Bearing		Frequency			Frequency			Frequency	
0/360		6.3%	4.7%	6.4%	5.6%	7.7%	4.2%	4.8%	4.1%
23		3.4%	3.0%	2.6%	4.6%	2.1%	2.8%	4.0%	2.9%
45		3.1%	2.9%	2.5%	4.8%	1.6%	3.4%	3.0%	3.4%
68		2.8%	4.0%	2.3%	4.2%	1.2%	3.0%	4.7%	3.0%
90		8.1%	7.8%	4.0%	10.7%	2.7%	5.5%	10.4%	5.6%
113		4.4%	4.3%	1.9%	7.2%	1.1%	2.6%	5.1%	2.6%
135		5.9%	4.7%	1.3%	6.7%	2.3%	2.9%	5.0%	2.9%
158		3.5%	3.4%	1.8%	4.1%	1.9%	2.5%	3.4%	2.5%
180		2.5%	3.5%	1.9%	2.7%	1.3%	3.5%	3.8%	3.5%
203		0.9%	1.1%	1.6%	0.6%	0.8%	1.2%	0.7%	1.2%
225		1.7%	2.2%	2.8%	1.1%	2.9%	2.4%	1.3%	2.5%
248		1.7%	3.5%	3.3%	0.6%	3.4%	5.3%	1.6%	5.3%
270		7.5%	11.6%	12.5%	2.6%	15.8%	18.4%	5.8%	18.6%
293		5.8%	6.6%	8.5%	2.4%	10.9%	10.5%	4.9%	10.6%
315		6.7%	4.4%	9.2%	4.5%	11.7%	4.5%	4.4%	4.5%
338		4.3%	3.9%	4.3%	3.9%	5.2%	3.7%	4.3%	3.7%
Calm		31.6%	28.3%	33.3%	33.7%	27.4%	23.6%	32.9%	23.1%
N	293° to 68°	32.3%	29.6%	35.7%	30.0%	40.4%	32.1%	30.0%	32.2%
S	113° to 248°	20.6%	22.7%	14.5%	22.9%	13.7%	20.4%	20.9%	20.6%
NW	270° to 360°	30.5%	31.3%	40.9%	19.1%	51.3%	41.3%	24.1%	41.5%
SE	90° to 180°	24.3%	23.7%	10.9%	31.4%	9.3%	17.0%	27.7%	17.2%

Seasonal and interannual variation in wind conditions directly affect water level elevation, wave generation, and current patterns along the coast of the Alligator Rivers Region. In particular, winds, waves and water level variation drive the nearshore currents and determine the direction of sediment transport along the coast away from the river mouths. Two propositions require testing in this context:

- First, it is proposed that marked erosion of the shoreline, from the Mary River to east of the Wildman River, may be associated with recent, subtle change in the frequency of WNW wind activity and the duration of prevailing onshore winds during the historical period.
- Second, but of no less significance, it is proposed that the geometry of van Diemen Gulf may amplify the effects of regional climate change, such as that associated with ENSO events. This would mean that monitoring climate and sea level change in the Gulf would have far reaching ramifications for our understanding of climate change throughout the Australia Pacific Region.

4 Sub-projects

The objectives mentioned above can be itemised into a number of sub-projects. Some of these have been started whilst others will proceed as funding and collaboration come available.

4.1 Wind direction and velocity

Seasonal and interannual shifts in average wind direction and velocity contribute to oceanographic processes, especially fluctuation in the wave regime and variation in water level around the shores of van Diemen Gulf. Hence analysis of existing wind records is fundamental to interpretation of coastal erosion, including destruction of mangrove communities; water levels within the estuarine reaches of rivers; the incursion of tidal creeks into freshwater meadows and billabongs of the floodplains. An examination of short-term variation in local wind direction and velocity around van Diemen Gulf has been initiated using wind data supplied by the Bureau of Meteorology (Darwin). An analysis of the data is being conducted in two parts. The first involves compilation of descriptive statistics for weather stations located in the Region and includes description of time series. Second, spatial variation in the wind records is being established to determine characteristic patterns of variation. Results from the analyses will provide a context for oceanographic processes and descriptions of shoreline movement.

4.2 Tides of van Diemen Gulf

The National Tidal Facility (NTF) has in progress at the moment a project called the 'Australian Baseline Sea Level Monitoring Project', under the Greenhouse Climate Change Core Research Program. The project supports an array of 14 SEAFRAME (Sea Level Fine Resolution Acoustic Measuring Equipment) stations at various locations around Australia which record sea level to an accuracy of better than 1 mm. These stations stand alone: recording water level, weather, as well as other information which can be downloaded using a satellite transmitter. The nearest SEAFRAME station to the Alligator Rivers Region is the Darwin gauge, which began recording data in May 1990. The dataset contains sea level data and meteorological data from Darwin.

There are no permanent gauges in van Diemen Gulf waters. Tide gauges that are closest to the Gulf and thus Alligator Rivers Region are the Darwin SEAFRAME gauge, the Darwin tide gauge which was in operation from 1/12/1958 to 31/12/1994, and the Melville Bay Gove Island tide gauge.

At least three, high-resolution tidal stations would be required to accurately measure and describe the tides in van Diemen Gulf. Additionally, establishment of tide stations is necessary to enable broad regional change in water levels to be determined within van Diemen Gulf. These should be located in the vicinity of Cape Hotham, Field Island and Cape Don.

4.3 Sea level variation in van Diemen Gulf

Sea level fluctuations directly affect wetlands along the coastal margins; for example, through increased erosion and loss of mangrove vegetation (Woodroffe & Mulrennan 1993). Establishment of tidal stations therefore should be an important consideration. It would enable determination of the characteristic patterns of spatial and temporal variation in sea level around the shores of van Diemen Gulf in response to seasonal, interannual and other short-term variations in climate. However, this is a large commitment. This is an important consideration because the record also may be affected by interannual variations in climate, such as those due to ENSO events, in the wet-dry tropics of northern Australia.

Bayliss et al (1997) examined tide gauge records from Darwin Harbour dating from 1959 to 1992. These records indicated that there may have been a slight variation in sea level at the Darwin station during the period of record, at rates between approximately 0.10 mm and -0.17 mm per year. This may appear insignificant but it would cause approximately 27 m of shoreline fluctuation on sandy coast. There is a 1:100 ratio between sea level change and shoreline response on such beaches (Bruun 1962, 1983, Komar 1996). Unfortunately, the conversion ratio for muddy coast is not as well defined as that for sandy coasts. Further, there is a need for caution in interpreting the short tidal record because the trend is very low and the gauging station is located outside van Diemen Gulf.

4.4 Bathymetry

The bathymetry of van Diemen Gulf is shown on Hydrographic Chart AUS. 308, Goulburn Islands to Melville Island, which was published in 1968 from information gathered prior to 1966. The scale of the chart is 1:300 000. In a 'caution' on the chart, a note points out that:

> van Diemen Gulf and the waters adjacent to the north coast of Melville Island and the east coast of Vashon Head have not been properly surveyed. In these areas less water than charted may exist.

Detailed knowledge of the Gulf bathymetry is fundamental to understanding the way in which the shorelines become reconfigured under changing hydrodynamic conditions. Given that the chart information is dated, the scale of resolution coarse and that more detailed information would be required to assess bathymetric changes within the Gulf, government agencies should be encouraged to commission a resurvey of the bathymetry of van Diemen Gulf.

4.5 Water circulation in the Gulf

Accurate description of water circulation is fundamental to an understanding of sediment transport mechanisms and pathways, particularly dispersal of the suspended material transported into the Gulf basin by fluvial processes. Further, the water circulation patterns provide some explanation of where and why coastal erosion is taking place around the shores of the Gulf.

There are several methods of determining water circulation patterns in large water bodies such as van Diemen Gulf. They may be inferred from the distribution of sediments; estimated by numerical modelling based on basin bathymetry, the wind regime and tidal fluctuations; interpreted from sequential satellite images that record major flood discharges into the basin; and mapped by direct measurement of the currents through drogue tracking and current metering. Relative to the other techniques, numerical modelling of the water circulation patterns within the Gulf would provide an inexpensive first-order description of the gross circulation pattern and indicate key areas for the focus of more detailed, integrated field research.

Green (1998) completed a three-dimensional numerical model of the hydrodynamics of van Diemen Gulf. Several barotropic (tide driven) simulations were modelled to characterise circulation in the Gulf under a range conditions. Simulations initially modelled spring and neap tide cycles. They were then extended into average wind conditions, based onwind data from Darwin for 1996/97, during Wet and Dry seasons. Finally, a discharge was added into the Gulf from the South Alligator River to model variation of the hydrodynamics in the Wet season.

Results from the modelling indicate that the tidal wave entering through Dundas Strait drives the circulation in most of the Gulf. Motion in the open regions is generally bidirectional and symmetrical. Eddy formation occurs in the lee of Cape Don. The modelling indicated that residence times in the Gulf are in the order of several weeks under tidal influence. Low circulation in the eastern region of the Gulf provides rationale for the accumulation of fine sediments on the coastal margins and the development of broad floodplains. Multiple particle release and Lagrangian tracking demonstrated that motion of water in the eastern gulf is largely limited to a bidirectional movement in a localised area of approximately 30 to 60 km^2. In contrast to this, a contaminant release in the western region of the Gulf would be flushed through Dundas Strait within a week. Particles released into Clarence Strait travel northwards along the northwest side of the Gulf and out Dundas Strait.

4.6 El Nino–Southern Oscillation events

Allan et al (1996) provided a description of El Nino–Southern Oscillation phenomenon and further information may be obtained from the web pages of the Bureau of Meteorology (http://www.bom.gov.au). The Southern Oscillation is identified as the tendency of atmospheric pressure at stations in the Pacific to increase, while sea level pressures in the Region of the Indian Ocean decreases. The Southern Oscillation Index (SOI) describes the Southern Oscillation. It is defined approximately by the pressure difference between Tahiti and Darwin. Negative values of the SOI indicate El Nino episodes. 'The term El Nino refers to a sequence of changes in atmospheric circulations across the Pacific Ocean and Indonesian archipelago when warming is particularly strong (on average every three to eight years)' (Australian Bureau of Meteorology 1998).

In ENSO years there is a marked pressure difference between Tahiti and Darwin. Changes to the atmosphere and ocean circulation system at this time include:

- warmer than normal ocean temperatures across the central and southern tropics of the Pacific Ocean;
- increased convection or cloudiness in the central tropical Pacific Ocean;
- convection migrates from Australian/Indonesian region eastward to the central tropical Pacific Ocean; and
- weaker than normal (easterly) trade winds; and low negative values of the SOI (Australian Bureau of Meteorology 1998).

Seasonal and interannual shifts in average wind direction and velocity associated with atmospheric fluctuation between ENSO and anti-ENSO states is anticipated to contribute to oceanographic processes, especially fluctuation in the wave regime and variation in water level around the shores of van Diemen Gulf. The direction, duration and velocity of regional winds is directly related to the regional wave regime, nearshore water circulation and the set-up of water level along the coast. Fluctuations in sea level, temporal variation in wave regime and beach responses associated with, or at ENSO frequencies, have been reported from the Galapagos (Komar & Enfield 1987) and south-western Australia (Clarke & Eliot 1988).

It is reasonable to anticipate that similar variations in the oceanographic climate in van Diemen Gulf would be associated with ENSO related phenomena. The prevailing (most frequently occurring) winds switch from offshore easterly trade winds in anti-ENSO years (those with a positive SOI) to prevailing to prevalent onshore westerly winds during ENSO events. Research and management questions stemming from this are concerned with event frequency and duration, as well as whether the interannual variation is of sufficient amplitude and period to drive the salt water intrusion observed in the coastal wetlands over the past 50 years. Investigations currently being undertaken as part of the Coastal Monitoring Program have been constructed to answer these questions. The investigations have recently commenced and it is too early to provide detailed comment on results.

4.7 Shoreline movement and sediment movement

Shorelines are naturally dynamic, changing in response to variation in nearshore oceanographic processes. Where the coast is disturbed by human use, the changes may be perceived as a threat to property or resources. This has occurred on parts of the coast in van Diemen Gulf. Woodroffe et al (1986) and Woodroffe and Mulrennan (1993) describe shoreline movement in Chambers Bay, between Cape Hotham and Point Stewart from interpretation of aerial photography for the historical period 1942 to 1984. They identify a cellular pattern of erosion and deposition along the coast with local erosion of up to 20 m y^{-1} in some places. The rates of change are rapid and severe, and their cause largely undetermined.

The geographic significance of shoreline movement in the Gulf has yet to be investigated. There are several reasons why it should be attempted. At a local scale, alongshore variation in erosion and deposition may provide an appreciation of the direction of sediment transport, with deposition on the updrift side of coastal salients, such as rock outcrops, and erosion on their downdrift side. At a broader scale, cursory inspection of aerial photography indicates that changes may be systematically related to the distribution of rivers and tidal creeks, with the greatest erosion occurring updrift of the river mouths. In some circumstances, estimation of alongshore transport rates is possible from such observations and will provide an indication of how the coast is changing. In either case, coastal erosion depletes the protective fringe of mangroves. It leads to increased storm washover on the very low-lying coastal plain and landward extension of the intertidal salt flats. The monitoring program has been designed to examine these propositions and establish their relevance to wetland management in the Region. The mapping of the salt flats from aerial photography will provide information identifying possible loss of freshwater wetland, however, detailed and systematic analysis of coastal change has yet to be initiated.

5 Recommendations

Oceanographic investigations of van Diemen Gulf described above are a component of the Coastal Monitoring Program and must be considered in that light. The monitoring program was intended to provide baseline information of direct relevance to management of the Alligator Rivers Region, but also may be relevant to management of all coastal plains bordering the Gulf. Its recommendations remain to be fully and effectively implemented.

6 Acknowledgments

The authors would like to thank the Bureau of Meteorology for supplying wind data: Des Clarke (University of Wollongong) for undertaking the numerical analysis in progress; and Chari Pattiaratchi and Tim Green for examining the hydrodynamics of van Diemen Gulf. We particularly thank Ben Bayliss, Ray Hall, Dave Walden and Ann Bull for their contributions, as well as Max Finlayson for his provoking questions.

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Paper 5 Surface hydrology of the Alligator Rivers Region

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Abstract

Biophysical investigations are being undertaken as part of a program for assessment and monitoring of coastal change in the Alligator Rivers Region. The investigations were initiated by the Environmental Research Institute of the Supervising Scientist at Jabiru, in the Northern Territory of Australia. Review of the hydrological information collected in the Region has been undertaken, to provide a baseline of information for the monitoring program. It also enables assessment, monitoring and predictive modelling of the wetland, stream and river network of the Alligator River Region.

Stream gauging stations have been deployed throughout the Alligator Rivers Region since 1957. These have been identified, their distribution illustrated and the length of available record determined. The information provides a basis for hydrological modelling of stream flow in the Region. In addition to the stream gauging information, the hydrological modelling also requires an accurate tidal record for stations in van Diemen Gulf. At present the network of tide gauging stations in the Northern Territory is insufficient to adequately describe tidal conditions along the coast of the Alligator Rivers Region.

Key words: Alligator Rivers Region, van Diemen Gulf, hydrology, tides, coastal monitoring

1 Introduction

The Alligator Rivers Region (fig 1) is a vast wilderness area of immense natural and cultural significance and encompasses the 20 000 km^2 of Kakadu National Park (Finlayson & von Oertzen 1996). It is approximately 150 km east of Darwin, in the Northern Territory of Australia. The Region stretches from rocky highlands to the south, through low relief plains, river floodplains, wetlands, deltaic floodplains to a narrow coastal plain on the shore of van Diemen Gulf (Wasson 1992). Low elevation throughout the Alligator Rivers Region determines that the Region is extremely susceptible to fluctuations in ocean water levels (Bayliss et al 1997). Studies of the neighbouring Mary River Region (Woodroffe & Mulrennan 1993) indicate that the estuarine reaches of these wetlands are the most dynamic sections. Here, the balance between ocean water levels and freshwater outflows affect a range of processes including salt water intrusion, sedimentation and tidal creek expansion.

A recommendation was made for development of a program to assess and monitor coastal change in the Alligator Rivers Region. This was made in recognition of the vulnerability of the Region to climate change (Bayliss et al 1997). The Environmental Research Institute of the Supervising Scientist coordinated development of the program. Knowledge of stream and wetland hydrology is integral to an understanding of processes affecting coastal stability.

Investigation of the hydrological record of the Alligator Rivers Region and analysis of the available information has been undertaken as part of the Coastal Monitoring Program.

Hydrological information is required for analysis and modelling of:

- inundation patterns — freshwater and saline;
- wetland, stream, river dynamics of the coastal plain;
- estuarine morphodynamics;
- water quality conditions, including salt wedge intrusion;
- vegetation water supply.

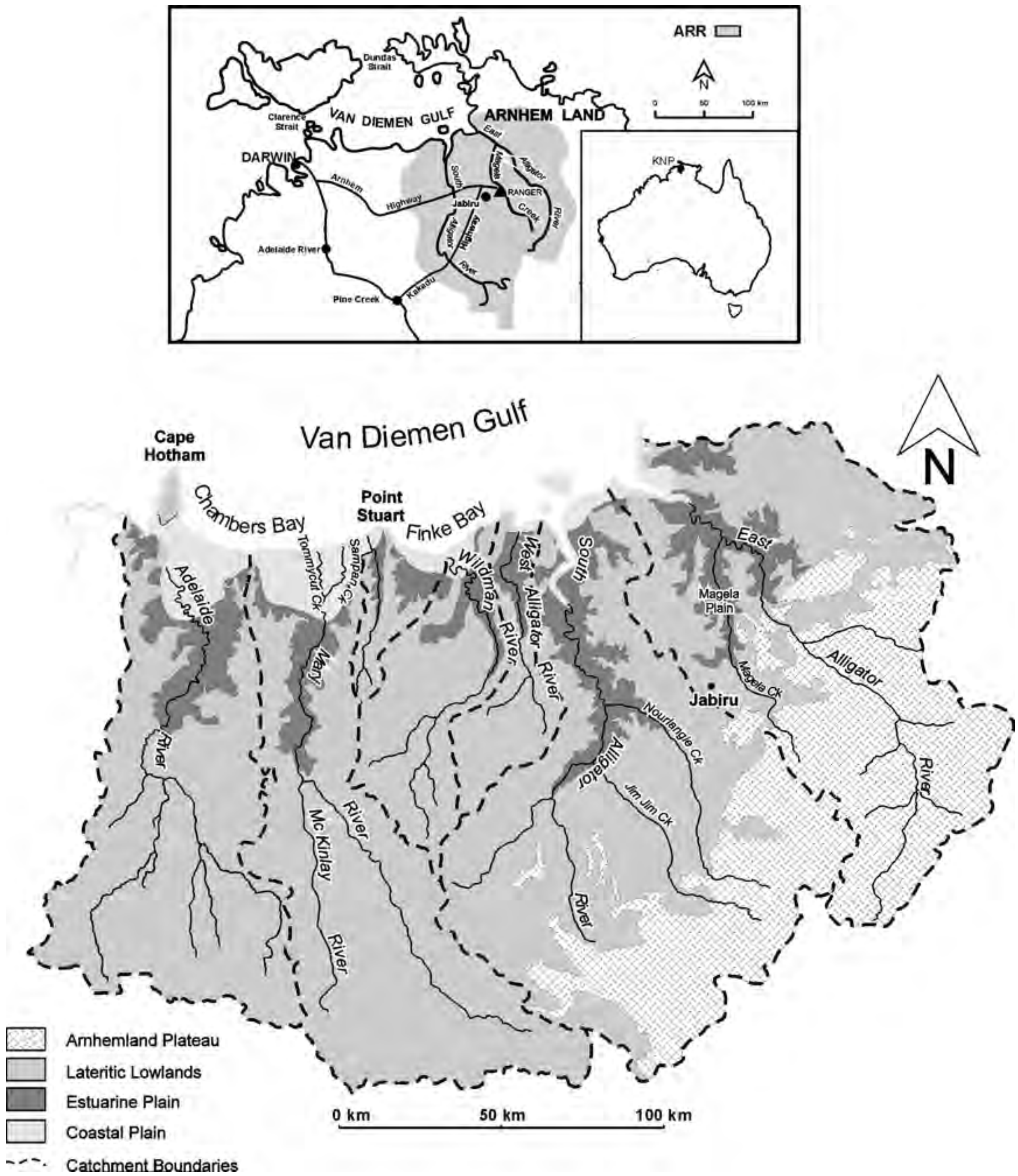

Figure1 Location diagram for the Alligator Rivers Region

Types of information required to achieve desired modelling outcomes include:

- catchment topography, including streambed profiles;
- catchment or sub-catchment descriptors, including vegetation and surface sediments;
- rainfall distributions and interannual variability;
- atmospheric conditions, such as temperature, evaporation and humidity;
- streamflow gauging;
- tidal measurements — which act as boundary conditions at the downstream end of the catchment;
- secondary information such as water quality or suspended sediment measurements.

The level and type of hydrological information required depends upon the temporal and spatial scales of analysis or modelling. For example, modelling of water quality conditions may be undertaken specifically at individual sub-catchments by using topography, streamflow gauging, tidal measurements and water quality. Significantly more detailed reference information is required for compilation of more accurate models.

2 Aim and objectives

The aims of this paper are to determine:

- the extent of hydrological information available in the Alligator Rivers Region;
- requirements for further development of hydrological models of the wetlands of the Alligator Rivers Region.

Objectives required to achieve these aims are to:

- identify, list and summarise previous hydrological studies;
- identify agencies responsible for recording of hydrological data sets;
- collate metadata regarding hydrological data, particularly location and deployment period;
- define catchment areas, identifying historic change where possible;
- on the basis of catchment and sub-catchment areas, determine the relative coverage provided by the hydrological data;
- assess the information required for development of hydrological models for the wetlands of the Alligator Rivers Region;
- establish if available information is sufficient for verification or calibration of hydrological models.

3 Background

Knowledge of surface hydrology is a fundamental requirement for understanding the biophysical processes that characterise stream and wetland ecosystems. Effective management practices for aquatic ecosystems are often limited by inadequate understanding of the underlying hydrological processes (Winter & Llamas 1993). As recently as thirty years ago little was known about the hydrological characteristics of the rivers flowing to van Diemen Gulf (Kingston 1991).

The hydrology of the Alligator Rivers Region is incompletely defined due to the highly variable and dynamic nature of its climate. Historically, the Water Resources Division of the Northern Territory Department of Lands, Planning and Environment (WRD/LPE) maintained a number of hydrological gauging stations. Data was made available to the Environmental Research Institute of the Supervising Scientist in a systematic manner. Recently, a number of these stations have been phased out, with data acquisition and storage becoming less systematic. All data gathered is essential for the broader programs of the Environmental Research Institute of the Supervising Scientist, including mining impact assessment, wetland management and the Coastal Monitoring Program.

Some hydrological modelling was undertaken in the late 1970s and 1980s by the Environmental Research Institute of the Supervising Scientist and the Water Resources Division (Transport & Works 1979, 1980, 1982, Vardavas 1988, 1989a,b,c). In both instances the principal aim of hydrodynamic modelling was to provide baseline information for the management of Ranger Uranium Mine. The modelling was based on a concentrated study of the Magela Creek and its floodplain.

The understanding and modelling of surface hydrology in the Alligator Rivers Region is made difficult by factors such as the high interannual variability in the rainfall of the Region, a lack of data describing variation in climate and a poor knowledge of surficial sediment characteristics and distribution. In addition to this other factors greatly influence the water velocity, stream pattern and subsequent particulate deposition in billabongs and floodplains. For example, annual variation in the response of vegetation growth to water depth, the effects of introduced weeds such as *Salvinia molesta*, and re-establishment of thick grass mats following the eradication of feral buffalo all affect bed roughness and change the hydrodynamic properties of coastal wetlands.

4 Methods

4.1 Previously published hydrological information

Sources of reported information have been collated by the Environmental Research Institute of the Supervising Scientist through its role in wetland assessment and monitoring in the Alligator Rivers Region. Key hydrological questions for research and management have been determined from collated literature, previous hydrological studies, discussions with the Environmental Research Institute of the Supervising Scientist personnel, and through the directives of the vulnerability assessment report for the Alligator Rivers Region (Bayliss et al 1997).

4.2 Climate record

Rainfall and other climate data suitable for hydrological modelling is available from various government authorities and private companies that have operated within or near the Alligator Rivers Region. Government agencies contacted with regard to climate data were:

- Australian Bureau of Meteorology;
- Northern Territory Department of Lands, Planning and Environment;
- Parks Australia North.

At least, mining companies that have operated within the Alligator Rivers Region have collected rainfall records to assist with water management. Mining companies contacted to provide climate records were:

- Energy Resources of Australia (ERA), at Ranger Uranium Mine;
- Queensland Mines Limited (QML), at Nabarlek.

Metadata requested for each of the stations maintained by the mining companies included: location, length of record, instrumentation, data storage and download mechanism. An outline of the baseline climate record within the Alligator Rivers Region is contained in chapter 4.

4.3 Hydrological data sets

The Water Resources Division of the Northern Territory Department of Lands, Planning and Environment (WRD/LPE) has historically collected stream gauge data throughout the Territory. This system of gauges has been used to provide the baseline of stream gauging data. Water Resources Division provided the gauging metadata included within this paper. This includes location, deployment period and a listing of any additional instrumentation for water quality or sediment measurement.

5 Review of published literature

5.1 The drainage network

Four major rivers drain the Alligator Rivers Region and flow into van Diemen Gulf. The South Alligator and East Alligator Rivers drain the larger portion of the Region, with the smaller West Alligator and Wildman Rivers draining the northwestern portion of the Region. 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).

Wet season runoff from the escarpment flows to the adjacent lowlands via spectacular waterfalls such as Twin Falls, Jim Jim Falls, Barramundi Falls and Magela Falls. Where an escarpment is not present, such as on the South Alligator River between Coronation Hill and Gunlom, the rivers flow onto the lowlands through valleys bounded by plateau outliers, hills and ridges (East 1996).

Below the escarpment, the main rivers have a freshwater flow regime upstream and a tidal estuarine reach downstream. Spring tidal range in van Diemen Gulf is 5 to 6 m. It affects the river flow up to 105 km inland (Woodroffe et al 1989). During the Wet season, water in the estuaries is predominantly fresh, becoming more saline in the Dry season when runoff from the catchment declines and eventually ceases.

In the upper reaches the main rivers flow in braided sand channels through broad shallow valleys flanked by long, low gradients. Wet season rain fills the creeks and rivers, and freshwater covers the extensive floodplain to a depth of several metres. A few months after conclusion of the Wet season, freshwater flow ceases through most of the lowland creeks. Floodplains dry out, isolating a few permanent swamps and water bodies, locally called billabongs, in deeper sections of channels and on the floodplains.

Below the sand channel tract, the main rivers and tributaries are commonly incompetent. A stream becomes incompetent when its erosional power declines below the depositional rate of the sediment it carries, causing siltation (Williams 1979). The rivers abandon a defined channel and flow into extensive shallow flood basins. Freshwater flood basins merge downstream with broad floodplains flanking tidal river channels and extend to the coast. Tidal channels are typically separated from upstream flood basins by broad, low levees. The tidal river channels have a single broad meandering channel that may be many kilometres across at the mouth (East 1996).

The drainage network of the Region is not considered dense, reflecting the absence of impermeable soils (Chapman 1988). In general, a dense drainage network has a preponderance of impermeable soils. Kingston (1991) estimated the lag between rainfall and runoff as around two months, which supports the conclusion of Chapman (1988). Water storage areas in the generally permeable soils and deep sand beds of the creek channels are filled by initial rainfall (McQuade et al 1996). Once these storage areas are filled, runoff to the small streams is rapid.

Discharges at the mouths of the major rivers have not been measured because tidal conditions make hydraulic rating extremely difficult (McQuade et al 1996). Additionally, extreme flood events simply overwhelm the floodplains, making it difficult to distinguish between the river mouths and the ocean. Estimated total annual flows at the mouths of the South Alligator and East Alligator Rivers are 2730 and 2560 million cubic metres respectively. Estimated average annual flows for Magela and Nourlangie Creek systems are 244.5 and 678.8 million cubic metres respectively (Christian & Aldrick 1977). However, subsequent observations indicate these estimates considerably underestimate potential discharges during extreme events (Erskine & Saynor 2000).

5.2 Hydrology of the landform units

The land surface of the region consists of six major physiographic units, described by Williams (1969), Galloway (1976), East (1990) and Wasson et al (1992):

- a plateau and outliers of mainly resistant quartzose sandstone;
- an erosional plain and isolated hills and strike ridges;
- intermittently inundated floodplains;
- low lying seasonally inundated flood basins;
- deltaic estuarine floodplains; and
- a narrow coastal plain.

In describing the hydrology of the Region, McQuade et al (1996) make reference to three major physiographic land surface units summarised as:

- escarpment
- lowlands
- floodplains.

The classification system of McQuade et al (1996) is used here for purposes of convenience.

5.3 Escarpment area

Arnhem Land plateau is formed predominantly of sandstone and to a lesser extent conglomerate. It has an overall height of about 300 metres (Nanson et al 1990). About one third of the plateau is bare rock. Plateau soils are typically shallow (<1 m deep) and are sandy and skeletal (Wasson 1992). The sandstone has well-developed horizontal bedding and vertical joints which have directed surface drainage giving an often deeply incised trellis drainage pattern. Surface runoff is usually rapid, being promoted by the bare rock, thin soils and deeply incised bedrock channels (Nanson et al 1990, Roberts 1991). Water storage is restricted to the faults and fracture systems that fill during the Wet season and are typically drained within two months after the end of the Wet season. The groundwater resource of the rock material is considered to be poor to negligible (McQuade et al 1996).

5.4 Lowland area

The lowlands comprise gently undulating erosional plains with slopes as little as 1 in 1500, which is conducive to the formation of braided streams and billabongs. At the beginning of the Wet season, rainfall rapidly infiltrates the soil and begins to recharge the groundwater table. This may fall between 2 and 4 m during the Dry season (Chapman 1988). As the Wet season progresses a perched water table develops, leading to surface runoff during intense rainfall events. Intense rainfall events are accompanied by rapid increases in creek flows which are superimposed on a Wet season base flow of less than 5 $m^3 s^{-1}$ that usually ceases within a few months of the end of the Wet season (McQuade et al 1996).

5.5 Floodplain area

Floodplains of the Region typically have black cracking clays overlying estuarine deposits. These clays have high infiltration rates that are attributed to desiccation cracks which may be more than 1 metre deep (Kellett et al 1979). Initial rains of the Wet season tend to seal the soil surface, reducing the infiltration rate and allowing water to pond (Kingston 1991, McQuade et al 1996). Water typically begins to enter the floodplains through ephemeral creeks during January. It is immediately impeded by dense vegetation, which in combination with the flat topography, results in water velocities of less than 0.1 ms^{-1}. Flow from the creeks and surrounding lowlands provide the majority of fresh water to the floodplains rather than direct rainfall (Vardavas 1989a). Water on the floodplains flows through a network of billabongs. The channels may become ill defined as water inundates the plain to a depth of several metres. Depending on the annual rainfall and the length of the Wet season, the number of billabongs on the floodplains that hold water throughout the Dry season varies markedly from year to year (McQuade et al 1996). Vardavas (1989a) found vegetation growth on the floodplain to be an important factor in the flow of water during the period of inundation. The occurrence of plant species in different habitats on the floodplains during the Wet season is determined primarily by the water depth and period of inundation by floodwaters (Finlayson et al 1989). This gives rise to a variability in vegetation growth from year to year which affects the surface roughness of the floodplain. Such variability greatly reduces the accuracy of hydrological modelling of the floodplain (Gurnell & Midgley 1994).

5.6 Inundation of the plains

Kingston (1991) has provided a comprehensive description of the inundation of the Alligator Rivers Region plains. Following is an extract written by Purich (1965) from this work:

> A dearth of accurate information on the flooding behaviour of the coastal plains, with their rich biota of swamp-dwelling mammals, reptiles, birds and fish prompted the Water Resources Branch of the Northern Territory Administration to install automatic water level recorders at twelve stations on the floodplains in 1956. It was well known that the low, flat topography of the coastal plains and the seasonally wet monsoonal climate produced widespread and prolonged flooding, but for just how long, and to what depth the plains flooded, and with what frequency, were questions that remained unanswered.

In the precipitation-dominated sectors of the coastal plains, flooding is a function of topography, antecedent soil moisture content, and rainfall intensity and duration. Runoff is a residual quantity; that is to say, except when rainfall is intense, runoff is the amount of water left once evaporation, replenishment of soil moisture, use by vegetation, and infiltration are satisfied. Thus when rainfall is low, runoff is disproportionately much lower. Runoff responds substantially two to three months after the rains begin, after the soil moisture needs and evaporation are adequately satisfied.

If 150 mm of rain are needed to moisten and seal the cracking clay soils of the coastal plains, then areas that are subject to inundation by direct rainfall, such as many of the ill-drained coastal plains, may start to pond water well ahead of peak flow in the rivers or in the creeks draining onto the fringes of the plain. The general pattern for these maritime plains is for the coastal reaches to be inundated by direct rainfall, and for the headward reaches to be inundated by local runoff and periodic overflow from the principal river.

6 Coastal and estuarine processes

Processes of floodplain and river mouth sedimentation vary from one river to another according to interplay of tidal and Wet season flood behaviour. Flooding of the rivers of the Northern Territory is regulated by the strongly monsoonal climate of the Region. During the Wet season, groundwater storage builds steadily so that maximum runoff normally occurs late in the season, conveying sediment from slopes downstream into the tidal rivers. Geomorphologic evolution of the tidal rivers and floodplains is regulated by the total volume of floodwater and sediment entering the tidal system late in the Wet season, and by the interaction of fluvial floods and tides in arresting and redistributing the sediment (Chappell & Woodroffe 1985).

Prevailing northwesterly winds generate longshore currents with a net flow from west to east. Littoral drift of sediment across the river mouths will modify the impact of tides. The channel resistance created in the mouth will attenuate the height to which the tide rises on the landward side in response to the harmonic motion in the open sea. Further constriction by the growth of coastal barriers may inhibit tidal penetration almost completely. As tidal capacity is lost to siltation the semi-diurnal tidal flow will decrease and the tidal channel will, in turn, fail to maintain itself. The South Alligator and East Alligator Rivers have substantial catchments of high runoff country, the escarpment country, and enough net seaward flow to prevent closure of their channel mouths. Other streams, including the Mary and Wildman Rivers, historically have been constricted at their mouths. However, this may not presently be the case.

High tide in the East Alligator River is up to one metre higher than on the large tracts of the Magela plain. A barrier across the Magela plain embayment was formed by the spill of the East Alligator River. With a high tide of 3.8 m, this is the level to which the ground has been raised at the Magela outlet by sediment of estuarine origin. Levees along the South Alligator have occluded the outlets of Jim Jim Creek and Nourlangie Creek creating extensive paperbark swamps.

6.1 Hydrological modelling of Magela Creek floodplain

Vardavas (1989a & 1989c) provides details of the modelling of Magela Creek undertaken by the Environmental Research Institute of the Supervising Scientist in the late 1980s.

The following is an extract from these sources:

> A daily rainfall-runoff model has been developed (Vardavas 1988) as part of an overall contaminant transport model to predict the fate of contaminants that may enter the surface waters of the Magela Creek and its floodplain from the Ranger mine. A simple water balance model was developed which uses daily rainfall, averaged over the Magela catchment, and monthly-averaged daily evaporation to predict the daily discharge at the catchment outlet.
>
> The rainfall-runoff model was designed to match the creek response on a daily time scale since flow rates can change rapidly during periods of intensive rainfall eg from 10 $m^3 s^{-1}$ to 1000 $m^3 s^{-1}$ over a few days. It was validated by its ability to predict the measured daily discharge at the Magela catchment outlet over four years.

Surface runoff modelling was extended to simulate the water budget of the whole Magela floodplain (Vardavas 1989a). This model provides daily estimates of the volume of surface water on the floodplain and the discharge rate at the outlet channel. The model has been validated by examining its ability to predict the measured daily water depth at the floodplain's outlet channel for twelve years for which full data sets are available. It does so successfully, with an average error of 16%, using a single set of nine parameters selected using an optimisation technique (Vardavas 1989b).

The model can be used to generate the average water depth and discharge at the outlet channel given daily rainfall data, monthly evaporation and daily Magela Creek discharge. In the absence of Magela Creek flow data the daily rainfall-runoff model can be used to estimate the discharge from Magela Creek from daily rainfall data averaged over its catchment.

The model results indicate that there is a correlation between early Wet season rainfall and channel roughness. One factor affecting roughness is the density of vegetation cover lining the bed and banks of the outlet channel. This is consistent with a correlation between early Wet season rainfall and seed germination on the floodplain. In turn, the rate of discharge from the floodplain determines the amount of water that persists on the floodplain during the Dry season. The surviving water bodies play a vital role in sustaining land animals, large numbers of birds, fish and other aquatic organisms during the Dry season. Seed germination in the early Wet season therefore may play a key role in the Dry season ecology of the floodplain by controlling discharge from the floodplain.

A simple gauge height — discharge relationship for the outlet channel of the floodplain is not possible due to large seasonal changes in the standing crop within the channel. Further, the rating curve is a looped curve, with rises and falls governed by events occurring during the early Wet season each year. Due to these conditions, a water balance model for daily rainfall-runoff at least is required to estimate the amount of water and waterborne contaminants that enter and leave the floodplain over a given period.

A quick estimate of the annual volume of water that enters and leaves the floodplain is often needed before a detailed analysis can be made of the fate of incoming material loads. To this end the model has been used to obtain a correlation between the accurately known annual discharge from Magela Creek at Jabiru and that of the floodplain outlet. A strong correlation was found, with the long-term average annual floodplain discharge being about 1.5 times larger than that from the Magela Creek catchment above Jabiru.

The NT Water Resources Division performed further modelling of Magela Creek in 1979. Details of this modelling can be found in volume 1, chapter 6 of *Uranium Province Hydrology* (Transport & Works, Dept of 1979, 1980, 1982).

7 Hydrological datasets

7.1 Stream gauging

At least 39 PAWA gauging sites (river and coastal) have been identified as being of use to the project. Data from the gauge on the Magela floodplain and gauges on other creeks presently accessed by the Environmental Research Institute of the Supervising Scientist has been updated. The principal custodian of gauge data in the Northern Territory is the Water Resources Division of the Department of Lands, Planning and Environment (WRD/LPE). Stream gauging in the NT commenced in 1952 and by 1984 the WRD operated a total of 244 gauge stations and 91 pluviograph stations. A large number of stations were closed in 1986–87 following the withdrawal of Commonwealth financial assistance. All gauging sites and stations both operational and discontinued within the Alligator Rivers Region have been identified (annex 1). Gauging stations still in operation in the Alligator Rivers Region are listed in table 1.

Table 1 Alligator Rivers Region stream gauging stations presently in operation

Station id	Station name	Commence	Cease
G8190001	West Alligator River at upstream Arnhem Highway	7/15/76	
G8200045	South Alligator River at El Sharana (‘c’)	8/18/58	
G8200049	Koongarra Creek near Nourlangie Rock	3/9/77	
G8200052	South Alligator River at Coronation Hill	12/4/85	
G8200080	Tommycut Creek upstream Crabbers Camp	12/18/95	
G8200083	Catchment G at Kapalga Research Station	10/7/92	
G8200084	Catchment C at Kapalga Research Station	10/19/92	
G8200085	Catchment E at Kapalga Research Station	12/16/93	
G8200112	Nourlangie Creek at Oenpelli Road crossing	11/11/60	
G8210007	Magela Creek at upstream Bowerbird Waterhole	11/11/77	
G8210009	Magela Creek at downstream Jabiru	9/24/71	
G8210010	East Alligator River at 12 Deg 43 Min South	11/3/71	
G8210016	Cooper Creek at Mt. Borradaile	11/24/79	
G8210017	Magela Creek Plains at Jabiluka Billabong	1/13/73	
G8210019	Magela Plains at outflow main channel	11/22/74	
G8210024	Cooper Creek at downstream Nabarlek	12/14/77	
G8210028	Magela Creek at Arnhem Border site	12/13/78	
G8210042	Magela Creek at Mine Valley	1/1/80	
Swift Creek	Swift Creek downstream Jabiluka	1/12/98	
East Trib	East Tributary of Swift Creek	1/12/98	
Upmain	Upper Swift Creek	1/12/98	

Stream gauging stations in the Alligator Rivers Region that have been discontinued but have 10 to 20 years of record and more than 20 years record are respectively listed in tables 2 and 3.

Table 2 Discontinued Alligator Rivers Region gauging stations with more than 20 years of record

Station id	Station name	Commence	Cease
G8190072	Swim Creek at Wildman Road	10/30/57	12/3/86
G8200041	South Alligator River at bridge site	8/3/69	7/4/90
G8200044	Goodparla Creek at Coirwong Gorge	10/3/66	8/11/93
G8200046	Deaf Adder Creek at Coljon ('c' Part)	8/22/72	1/18/94
G8200081	South Alligator River at West Plains	9/24/58	12/4/86
G8200111	Jim Jim Creek at Oenpelli Road crossing	11/11/60	9/26/80
G8210001	Cooper Creek at Nimbuwah ('c')	10/5/66	8/4/93
G8210012	Gulungul Creek (Boggy Creek) at Georgetown crossing	11/4/71	8/13/93
G8210015	East Alligator River at upstream Cahills Crossing	8/21/72	8/5/93

Table 3 Discontinued Alligator Rivers Region stream gauging stations with 10 to 20 years record

Station id	Station name	Commence	Cease
G8190073	West Alligator River at upper reach	11/22/68	6/21/78
G8190077	Carmor Plains at plains	9/16/58	4/13/70
G8190080	West Alligator River at Red Lily Lagoon	9/25/58	6/7/68
G8200004	Jim Jim Creek at above Five Sisters	8/24/74	12/8/86
G8200042	Jim Jim Creek at Graveside Gorge West Arm	11/19/68	11/13/85
G8200043	South Alligator River at upstream Kapalga	10/25/67	9/23/77
G8200047	Hickey Creek at Sawcut Gorge ('c' Part)	8/18/72	12/9/86
G8200048	Baroalba Creek at Oenpelli Road crossing	8/17/72	9/11/85
G8200082	South Alligator River at Boggy Plains	10/11/58	9/23/77
G8210005	Boggy Creek at Ranger Mines Site 2	12/20/70	8/25/80
G8210011	Tin Camp Creek at downstream Myra Falls	11/15/71	5/12/82
G8210039	East Alligator River at Turkey Dreaming	11/23/79	8/10/93

For a number of years the Environmental Research Institute of the Supervising Scientist has been receiving gauge data for the Magela Creek and floodplain as part of the ongoing research in these areas. More recently gauge data has been obtained for the upper South Alligator River for studies relating to the proposed establishment of mining at Coronation Hill. These data requests have been made by individual staff on an 'as need' basis for the specific research project Gauging stations in the Alligator Rivers Region for which the Environmental Research Institute of the Supervising Scientist currently has data are listed in table 4.

7.2 Tide measurement

Tidal measurement is critical for hydrological modelling in the Alligator Rivers Region, as the tidal conditions dominate the downstream reaches of all the major rivers. Historically, the Water Resources Division operated up to nine permanent tide gauges throughout the Northern Territory. Many of these tide gauges have since been phased out, with only two gauges still operating. The majority of tide gauges were deployed less than 20 years. A gauge is currently operating in Darwin Harbour, and has been deployed there for approximately 39 years. A gauge is also operating in Melville Bay, Gove. It has been operational for approximately 35 years.

Table 4 Alligator Rivers Region stream gauging stations for which the Environmental Research Institute of the Supervising Scientist currently has data

Station Id	Station name	Commence	Cease
G8200045	South Alligator River at El Sharana ('c')	8/18/58	
G8200052	South Alligator River at Coronation Hill	12/4/85	
G8210009	Magela Creek at downstream Jabiru	9/24/71	
G8210017	Magela Creek Plains at Jabiluka Billabong	1/13/73	
G8210019	Magela Plains at outflow main channel	11/22/74	
G8210024	Cooper Creek at downstream Nabarlek	12/14/77	
G8210042	Magela Creek at Mine Valley	1/1/80	

The National Tide Facility at Flinders University, Adelaide operates a SEAFRAME gauge in Darwin Harbour. It has been installed since 1990 and records water level at six minute intervals. The gauge is located close to the Water Resources Division tide gauge.

Operational and discontinued tide gauges in the Northern Territory are listed in table 5. It may be noted that there have never been any tide gauges operational inside van Diemen Gulf, the tides of which directly affect the Alligator Rivers Region.

Table 5 Operational and discontinued Water Resources Division tide gauges in the NT

Station id	Station name	Commence	Cease
G8150029	Darwin Harbour tide at Fort Hill Wharf	1/1/59	continued
G8220001	Aurari Bay tide at Marligur Ck	2/11/78	2/12/86
G8260015	Melville Bay tide at Conveyor Wharf	9/5/80	continued
G8160007	Snake Bay tide at Melville Is	16/10/79	29/10/86
G9290239	Milner Bay tide at under conveyor	27/6/65	13/8/87
G9290009	Bartalumba Bay tide at Kailia Jetty	30/7/71	5/11/73
G9070122	Centre Is tide at Gulf of Carpentaria	4/12/72	21/8/87
G8260216	Melville Bay tide at Drimmi Head	5/12/63	26/6/81
G8130003	Port Keats tide at Dee Ck Landing	6/9/79	6/11/86

7.3 Secondary observations

Some stream gauging stations measuring sediment and other water quality parameters for specific project purposes have been operated in the Alligator Rivers Region. Most measurements have been of suspended sediment although a small number of bed load measurements have been made. Other studies of erosion and sediment transport in the Alligator Rivers Region include Duggan (1985), Nanson et al (1990), Roberts (1991), Wasson (1992) and Woodroffe et al (1989). Gauging stations identified as having water quality and/or sediment data are listed in table 6.

Table 6 Gauging stations in the Alligator Rivers Region recording water quality or sediment data

Station id	Station name	Water Q	Sediment
G8200001	Mt. Brockman at Nourlangie Rock Springs	Yes	No
G8200004	Jim Jim Creek at above Five Sisters	Yes	No
G8200042	Jim Jim Creek at Graveside Gorge West Arm	Yes	No
G8200043	South Alligator River at upstream Kapalga	Yes	No
G8200044	Goodparla Creek at Coirwong Gorge	Yes	Yes
G8200045	South Alligator River at El Sharana ('c')	Yes	No
G8200046	Deaf Adder Creek at Coljon ('c' Part)	Yes	Yes
G8200047	Hickey Creek at Sawcut Gorge ('c' Part)	Yes	Yes
G8200048	Baroalba Creek at Oenpelli Road crossing	Yes	No
G8200049	Koongarra Creek at near Nourlangie Rock	No	Yes
G8200081	South Alligator River at West Plains	Yes	No
G8200087	Nourlangie Creek at Safari Camp	Yes	No
G8200111	Jim Jim Creek at Oenpelli Road crossing	Yes	No
G8200112	Nourlangie Creek at Oenpelli Road crossing	Yes	No
G8210001	Cooper Creek at Nimbuwah ('c')	Yes	Yes
G8210005	Boggy Creek at Ranger Mines Site 2	Yes	No
G8210015	East Alligator River at upstream Cahills Crossing	Yes	No
G8210016	Cooper Creek at Mt. Borradaile	Yes	No
G8210017	Magela Creek Plains at Jabiluka Billabong	Yes	Yes
G8210018	Magela Creek at Mudginberri Homestead	Yes	Yes
G8210019	Magela Plains at outflow main channel	Yes	No
G8210023	Magela Creek Plains at Island Billabong	Yes	Yes
G8210024	Cooper Creek at downstream Nabarlek	No	No
G8210026	Baralil Creek at Arnhem Highway crossing	Yes	Yes
G8210031	Magela Creek at Ja Ja Billabong	Yes	Yes
G8210033	Magela Plains at Nankeen Billabong	Yes	Yes
G8210100	East Alligator River at Second Gorge	Yes	No
G8210215	Baralil Creek at 1.3 km south of highway X-ing	Yes	Yes
G8210216	Baralil Creek at Goanna Billabong U/s Gulungul	Yes	Yes
G8210221	Corndorl Creek at Jim Jim Road	Yes	Yes
G8210222	Corndorl Creek at Arnhem Highway crossing	Yes	No
G8210223	Corndorl Creek at Corndorl Billabong	Yes	No
G8210226	East Alligator Plains at Oenpelli Mission	Yes	No
G8210227	Magela Creek at Buffalo Billabong	Yes	Yes

7.4 Catchment characteristics

The Environmental Research Institute of the Supervising Scientist continues to develop a spatial database describing the Alligator Rivers Region. Data is collected by both field survey and ground-truthed remote sensing. Establishment of a differential GPS station as part of the coastal assessment and monitoring program has enabled high accuracy position fixing. This technology has been applied to both current survey programs and historic surveys where the survey base station has been identified and fixed.

Surveys are undertaken for both the wetland and coastal monitoring programs, and are outlined within other sections of this report. Catchment characteristics that are of importance to the coastal assessment and monitoring program include:

- catchment topography, including streambed profiles;
- vegetation distributions, including mangrove patterns;
- surface sediments and geomorphic units.

8 Conclusions

The prime outcome of this paper is the identification of hydrological information for the Alligator Rivers Region and adjacent areas. Climate information has been identified as a project component of the Coastal Monitoring Program.

Stream gauging stations throughout the Alligator Rivers Region have been identified. Assessment of whether the network is sufficiently comprehensive should be balanced against the sub-catchment scale of any intended hydrological modelling.

Tide gauge recordings throughout the Northern Territory have been identified. No gauges have been established in van Diemen Gulf. Consequently, downstream tidal signals will be poorly represented for hydrological modelling. Development of an improved tidal signal should be undertaken using an oceanographic tidal model, verified by field deployed tide gauges.

Stream gauging stations that measure water quality or suspended sediment have been identified. These stations may be particularly of use for hydrological modelling which is intended to determine morphodynamics or water quality, and form an important part of the baseline hydrological information.

Catchment characteristic studies are in progress. Geomorphological studies have been reported by Erskine and Saynor (2000). Difficulties exist in defining the Region in a manner suitable for hydrological modelling due to the dynamic nature of the Alligator Rivers Region, including seasonal vegetation change and stream bed movement.

Further development of any hydrological models requires a more advanced identification of the model aim, and the scale over which the model is to be established. Sufficient baseline information is available to determine the maximum scale of this modelling.

9 Recommendations

9.1 Stream gauging stations

Recommendations to further advance the usefulness of the stream gauging database are to:

- define the location, type and scale of hydrological modelling anticipated to be undertaken for the Alligator Rivers Region. This will determine if the existing stream gauging network is sufficient to allow meaningful calibration or verification.
- identify locations of interest which have poor coverage from the existing system to improve coverage of the network of stream gauging

- prioritise the stream gauging stations, allowing possible re-establishment of disused stations
- arrange for the establishment of a suitable stream gauging network in conjunction with Water Resources Division.

9.2 Tide gauge stations

It is recommended that knowledge of tides in the Region be improved. This requires, at the minimum, tidal modelling through van Diemen Gulf correlated with information from tide gauges at Darwin and Snake Bay, Melville Island.

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Annex 1 All gauging sites and stations both operational and discontinued within the Alligator Rivers Region

Station id	Station name	Commence	Cease
G8190001	West Alligator River at upstream Arnhem Highway	7/15/76	
G8190002	Wildman River at Hungry Reach	4/15/82	4/15/82
G8190004	Wildman Lagoon at Cashew Farm	8/21/84	10/18/85
G8190072	Swim Creek at Wildman Road	10/30/57	12/3/86
G8190073	West Alligator River at Upper Reach	11/22/68	6/21/78
G8190077	Carmor Plains at plains	9/16/58	4/13/70
G8190078	Wildman River at Runaway Camp	9/19/58	3/22/66
G8190079	Alecs Water Hole, Wildman River	9/21/58	12/17/67
G8190080	West Alligator River at Red Lily Lagoon	9/25/58	6/7/68
G8190094	Swim Creek Plains at Lower Plains	9/28/60	8/2/67
G8190100	Wildman River at D/s Arnhem H/way bridge	1/26/91	4/13/91
G8200001	Mt. Brockman at Nourlangie Rock Springs	5/2/73	11/8/76
G8200004	Jim Jim Creek at above Five Sisters	8/24/74	12/8/86
G8200005	South Alligator Plains at causeway	7/11/75	12/21/78
G8200041	South Alligator River at bridge site	8/3/69	7/4/90
G8200042	Jim Jim Creek at Graveside Gorge West Arm	11/19/68	11/13/85
G8200043	South Alligator River at upstream Kapalga	10/25/67	9/23/77
G8200044	Goodparla Creek at Coirwong Gorge	10/3/66	8/11/93
G8200045	South Alligator River at El Sharana (‘c’)	8/18/58	
G8200046	Deaf Adder Creek at Coljon (‘c’ Part)	8/22/72	1/18/94
G8200047	Hickey Creek at Sawcut Gorge (‘c’ Part)	8/18/72	12/9/86
G8200048	Baroalba Creek at Oenpelli Road Crossing	8/17/72	9/11/85
G8200049	Koongarra Creek at near Nourlangie Rock	3/9/77	
G8200050	Kuntakinte Creek at Noranda Site 1	1/10/73	6/29/78
G8200051	Aray Creek at Noranda Site 2a	1/10/73	9/2/78
G8200052	South Alligator River at Coronation Hill	12/4/85	
G8200053	South Alligator River at Old Oenpelli Road crossing	11/4/82	11/7/89
G8200054	Tailings Creek at Black Valley	12/6/87	7/28/93
G8200055	Gerowie Creek at Goodparla Road crossing	11/4/82	11/4/82
G8200060	Waterfall Creek at UDP Falls	7/3/86	8/13/86
G8200080	Tommycut Creek upstream Crabbers Camp	12/18/95	
G8200081	South Alligator River at West Plains	9/24/58	12/4/86
G8200082	South Alligator River at Boggy Plains	10/11/58	9/23/77
G8200083	Catchment G at Kapalga Research Station	10/7/92	
G8200084	Catchment C at Kapalga Research Station	10/19/92	
G8200085	Catchment E at Kapalga Research Station	12/16/93	
G8200087	Nourlangie Creek at Safari Camp	10/10/58	3/15/63

Annex 1 cont

Station id	Station name	Commence	Cease
G8200111	Jim Jim Creek at Oenpelli Road crossing	11/11/60	9/26/80
G8200112	Nourlangie Creek at Oenpelli Road crossing	11/11/60	
G8200257	Jim Jim Creek at above falls	9/11/65	10/1/74
G8210001	Cooper Creek at Nimbuwah ('c')	10/5/66	8/4/93
G8210005	Boggy Creek at Ranger Mines Site 2	12/20/70	8/25/80
G8210007	Magela Creek at upstream Bowerbird Waterhole	11/11/77	
G8210008	Magela Creek at Bowerbird Waterhole	11/5/71	7/21/80
G8210009	Magela Creek at downstream Jabiru	9/24/71	
G8210010	East Alligator River at 12 Deg 43 Min south	11/3/71	
G8210011	Tin Camp Creek at downstream Myra Falls	11/15/71	5/12/82
G8210012	Gulungul Creek (Boggy Creek) at Georgetown crossing	11/4/71	8/13/93
G8210014	Magela Trib. & Upper Boggy Ck at Ranger Sites 4a & 11	11/17/71	1/10/74
G8210015	East Alligator River at upstream Cahills Crossing	8/21/72	8/5/93
G8210016	Cooper Creek at Mt. Borradaile	11/24/79	
G8210017	Magela Creek Plains at Jabiluka Billabong	1/13/73	
G8210018	Magela Creek at Mudginberri Homestead	11/6/78	12/6/86
G8210019	Magela Plains at outflow main channel	11/22/74	
G8210020	Magela Plains at east of Jabiluka Site 1	11/17/76	10/19/81
G8210021	Magela Creek Plains at NW of Jabiluka Site No.2	11/17/76	10/29/85
G8210022	Magela Plains at Pelicans Camp Site No 3	11/9/76	9/11/85
G8210023	Magela Creek Plains at Island Billabong	11/12/77	11/14/86
G8210024	Cooper Creek at downstream Nabarlek	12/14/77	
G8210025	East Alligator River at upstream confluence	11/30/77	2/10/80
G8210026	Baralil Creek at Arnhem Highway Crossing	4/20/78	11/18/86
G8210028	Magela Creek at Arnhem Border site	12/13/78	
G8210029	Magela Creek at West Arm — Behind Mt Brockman	12/9/78	9/24/82
G8210030	Magela Plains at 7J Billabong	11/10/78	9/11/84
G8210031	Magela Creek at Ja Ja Billabong	11/9/78	8/31/87
G8210032	Magela Creek at Leichardt Billabong	11/5/78	9/13/84
G8210033	Magela Plains at Nankeen Billabong	11/4/78	9/13/84
G8210034	Magela Plains at Marlow Swamp	11/9/78	9/11/84
G8210035	Magela Plains at West Plain Billabong	11/9/78	9/12/84
G8210036	Magela Creek at opposite Bowerbird Waterhole	12/4/78	6/13/80
G8210037	Cooper Creek at Rainbow Flat	11/21/79	9/4/85
G8210038	Cooper Creek at Upstream Birraduk	12/2/79	12/17/82
G8210039	East Alligator River at Turkey Dreaming	11/23/79	8/10/93
G8210040	East Alligator River at Barramundi Dreaming	12/2/79	10/24/84
G8210041	Magela Plains at tidal downstream outflow	11/29/79	3/13/86
G8210042	Magela Creek at Mine Valley	1/1/80	

Annex 1 cont

Station id	Station name	Commence	Cease
G8210043	Cooper Creek at downstream dam	8/23/80	2/16/82
G8210044	Birraduk Creek at upstream Cooper Creek junction	1/20/84	7/18/84
G8210045	Smith Creek at upstream Cooper Creek junction	3/7/84	4/11/86
G8210046	Nimbuwah Creek at upstream Cooper Creek junction	1/25/84	6/4/87
G8210047	Birraduk Creek at Camp Pleasant	12/5/84	12/3/86
G8210048	Cooper Creek at Crocodile Pond	12/6/84	7/15/87
G8210049	Cooper Creek at Intrusion Point	12/5/84	4/23/85
G8210050	Magela Plains at Bristol Site	4/9/79	7/22/79
G8210051	Buffalo Creek at The Rocks	1/10/85	7/3/90
G8210052	Kadjirrikamarnda at u/s road crossing	1/15/85	5/14/86
G8210053	Corndorl Creek at Mudginberri fence	1/23/85	4/18/86
G8210054	Cooper Ck (Sites 1a & 1b) at 0.2 km D/s Buffalo Ck conf.	3/22/84	2/19/86
G8210055	7J Creek at Lancon Gs.	2/12/83	2/14/86
G8210056	Cooper Creek [site 3a] at 0.3 km D/s Gs8210024	3/23/84	2/19/86
G8210057	Cooper Creek [site 4a] at 4 km D/s Gs8210024	2/3/84	4/11/86
G8210058	Cooper Creek [site 5a] at 9.5 km D/s Gs8210024	2/23/84	4/11/86
G8210059	Cooper Creek [site 6a] at 18.5 km D/s Gs8210024	3/20/84	3/20/84
G8210060	Cooper Creek [site 7a] at 2 km U/s Murganella Rd Xing	3/9/84	6/6/85
G8210061	Cooper Creek [site 8a] at 3.5 km D/s Murganella	3/16/84	1/19/85
G8210062	Swift Creek at Oenpelli Road crossing	3/1/84	3/23/88
G8210063	Cooper Creek Billabong 3a at D/s Smith Creek	12/6/84	4/30/85
G8210064	Cooper Creek Billabong 3b at U/s Gove Road	12/6/84	3/4/86
G8210065	Cooper Creek Billabong 4a at near Nimbuwah	12/5/84	9/26/85
G8210066	Cooper Creek Billabong 1a at U/s Gs8210024	4/30/85	4/30/85
G8210067	Magela Creek at Section 1a (Ranger Pump Stn)	2/11/83	4/5/88
G8210068	Magela Creek at Dye Sec.5a D/s Coonjimba Junc.	2/8/84	2/19/85
G8210069	Magela Creek at downstream sewage outfall	2/8/84	12/13/85
G8210070	Magela Creek at Dye Sec.8a D/s Gulungul Junc.	3/27/84	1/16/86
G8210071	Magela Creek at Dye Sec.9a D/s Corndorl Junc.	3/27/84	1/16/86
G8210072	Magela Creek at Dye Sec. 10a U/s Mudginberri	3/28/84	5/3/85
G8210073	Coonjimba Creek at Ranger Retention Pond	?	7/4/94
G8210074	Cooper Creek at Dead Tree Plains	1/15/86	7/14/87
G8210075	Willis Springs Creek at 3 km East Cooper Ck. crossing	4/9/87	9/15/89
G8210076	Cooper Creek at Gove Road crossing	6/4/87	6/4/87
G8210078	Magela Creek at Section 1c	1/30/86	3/11/86
G8210079	Magela Creek at Section 1b	1/18/86	3/11/86
G8210080	Gulungul Creek at outflow	2/3/86	1/31/86
G8210081	Gulungul Creek at Dye release point	1/21/86	2/6/86
G8210082	Cooper Creek at Section 0b	1/30/86	2/19/86

Annex 1 cont

Station id	Station name	Commence	Cease
G8210083	Cooper Creek at Murganella Road crossing	5/15/84	5/15/84
G8210084	Cooper Creek at Gove Road	5/15/84	5/15/84
G8210085	Cooper Creek at West Arm 2 Gauges	2/25/85	2/25/85
G8210086	Cooper Creek at Section 0c	2/1/86	2/19/86
G8210087	Magela Creek at road Xing Dye Section 11a	3/28/84	3/28/84
G8210088	Djalkmarra at release point inflow	1/17/86	2/5/86
G8210089	Magela Creek at 3 Croc Billabong	2/20/85	2/22/85
G8210090	Magela Creek at Corndorl Billabong inflow	3/13/85	3/15/86
G8210091	Buffalo Creek at Site 2	2/4/81	2/16/82
G8210092	Magela Creek at Corndorl Billabong outflow	3/13/85	3/13/85
G8210093	Coonjimba Creek at spillway Retention Pond No1	2/5/81	2/7/81
G8210094	Caramel Creek at Ore Body	1/13/89	2/6/90
G8210095	Caramel Creek at Sandfly Reach	1/13/89	2/6/90
G8210096	Popham Creek — Northern End	8/10/94	10/11/94
G8210097	Popham Creek — Middle Reach	8/10/94	10/11/94
G8210098	Popham Creek — Southern Reach	8/9/94	10/11/94
G8210100	East Alligator River at Second Gorge	6/9/66	10/2/73
G8210200	Georgetown Creek at upstream Georgetown Creek	6/2/81	10/8/83
G8210201	Georgetown Creek at Georgetown Billabong	10/6/78	10/8/83
G8210202	Georgetown Creek at Georgetown Creek West	6/2/81	10/8/83
G8210205	Djalkmarra Creek at Djalkmarra Billabong	10/17/78	5/2/85
G8210206	Djalkmarra Creek at downstream Evaporation Pond	6/2/81	10/8/83
G8210208	Coonjimba Creek at Coonjimba Billabong	10/6/78	5/2/85
G8210209	Gulungul Creek at Old Rd Xing D/s Arnhem Hwy	1/17/86	2/6/86
G8210210	Gulungul Creek at Arnhem Highway crossing	4/20/78	3/19/85
G8210211	Gulungul Creek at Gulungul Billabong	4/20/78	2/7/87
G8210215	Baralil Creek at 1.3 km south of highway X-ing	12/9/78	10/10/83
G8210216	Baralil Creek at Goanna Billabong U/s Gulungul	4/28/78	10/8/83
G8210217	Baralil Creek at N.E. Corner of lake	9/4/81	7/28/82
G8210218	Baralil Creek at downstream sewerage ponds	6/2/81	10/8/83
G8210219	Baralil Creek at East Branch	3/22/79	10/10/83
G8210220	Baralil Creek at West Branch	3/22/79	10/10/83
G8210221	Corndorl Creek at Jim Jim Road	4/21/78	10/10/83
G8210222	Corndorl Creek at Arnhem Highway crossing	4/27/78	10/10/83
G8210223	Corndorl Creek at Corndorl Billabong	4/28/78	9/8/84
G8210224	Corndorl Creek at Upstream Corndorl Billabong	3/22/79	9/8/84
G8210226	East Alligator Plains at Oenpelli Mission	10/16/64	9/28/73
G8210227	Magela Creek at Buffalo Billabong	10/18/78	8/13/85
G8210228	Magela Plains at Upper Island Billabong	11/10/78	9/11/84

Paper 6 History of land use and resultant environmental change in the Alligator Rivers Region

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Abstract

Environmental change initiated by a particular land use may influence future land management strategies for that area. Change, such as the introduction of pest species, altered fire regimes or environmental degradation may continue to impact upon the area long after the land use has changed. Understanding of the history of an area enables recognition of landscape differentiation and its underlying cause and provides baseline information for monitoring further change.

The Alligator Rivers Region of the Northern Territory is often the subject of intense political debate and public interest due to its diverse natural and cultural values and vast mineral wealth. Historical land use and potential environmental impacts in the Region have been collated here as part of a broader monitoring program that aims to assist land managers of today to make decisions for the future.

Key words: Alligator Rivers Region, Kakadu National Park, cultural values, land use, fire regimes, introduced pests, exploration, settlement

1 Introduction

The Alligator Rivers Region lies east of Darwin in the Northern Territory, and encompasses the catchments of rivers draining into van Diemen Gulf between the eastern bank of the East Alligator River mouth and Point Stuart (Finlayson & Eliot 1999). These rivers include Love Creek (Bijibiju) and the Wildman, West Alligator, South Alligator and East Alligator Rivers. Kakadu National Park is contained within the Alligator Rivers Region, as are several small settlements, the township of Jabiru and nearby Ranger uranium mine (fig 1). This report also includes adjacent land, taking in Gunbalanya, a township in Arnhem Land near the east bank of the East Alligator River and mines or pastoral properties adjoining the Alligator Rivers Region.

Pastoralism, gold and uranium mining have long been dominant land uses within the Alligator Rivers Region and adjacent land, while conservation and tourism have emerged as more recent influences. Aboriginal people own much of the land in the Region and continue to utilise the natural resources in a semi-traditional manner.

Land use in the Region has been varied and dynamic, but not without ecological cost. For example, the problems presented by introduced plant and animal species affect floodplain and upland habitats (Cowie & Werner 1993), with direct bearing on land use options for the future. Environmental change resulting from past and present land use must be better understood in order for land managers to effectively meet the challenges of the future.

2 Aim

The aims of this paper are to:

- Establish sources, types and availability of written and oral information concerning changes in land use;
- Identify processes for a comprehensive historical analysis of land use information and compilation of a data registry.

3 Background

3.1 Status and previous work

There are a number of diaries, historical records and reports available outlining the history of the Region and its development since settlement by non-Aboriginal people. The majority of records are written from human perspectives; human lives, activities and perceptions, both Aboriginal and non-Aboriginal. There is little or no emphasis upon environmental change associated with the social upheavals and economic development that has occurred in the Region over the last century or so.

Although there is much still to be done, anthropologists, welfare officers, church missionaries and others (Cole 1975, Levitus 1986) have documented social change and the cultural disruption of Aboriginal people in the Region following an influx of Chinese and Europeans from the late 1800s. A recent social impact study in Kakadu National Park included a review of the history of the Region from the Aboriginal perspective (Carroll 1996). Aboriginal rock art and Dreaming sites of the Arnhem Land Plateau are steadily being documented (Chaloupka 1993). The Cultural Resource Management unit of Parks Australia North in Kakadu is recording Aboriginal culture and traditions.

European activities and perceptions are documented in diaries and books published by explorers, missionaries, buffalo shooters, pastoralists and others who visited or lived in the Region (Leichhardt 1847, Stewart 1969, Cole 1988, 1992). Some of the mining and pastoral history has been documented (Jones 1987, Gillespie unpub). Scientific reports and contemporary literature provide information upon current land use, demography, future development proposals, and environmental change including mining impact, weed invasions and feral animals.

In order to determine the extent and type of environmental change, and its relationship with historical land use in the Region, it is necessary to collate information from the above sources, often 'reading between the lines' or approaching an original source from another perspective. Further oral recording is required to supplement the written material available.

3.2 Exploration

Ludwig Leichhardt was the first European to traverse the Alligator Rivers. In 1845 Leichhardt recorded numerous buffalo in the Region and met Aborigines who could speak English (Leichhardt 1847). It appears that Leichhardt travelled between Jim Jim Falls and Deaf Adder Creek, through the wetlands of Nourlangie and Magela Creeks to the shortlived British settlement at Port Essington. His favourable reports of the country encouraged interest in northern Australia (Christian 1973).

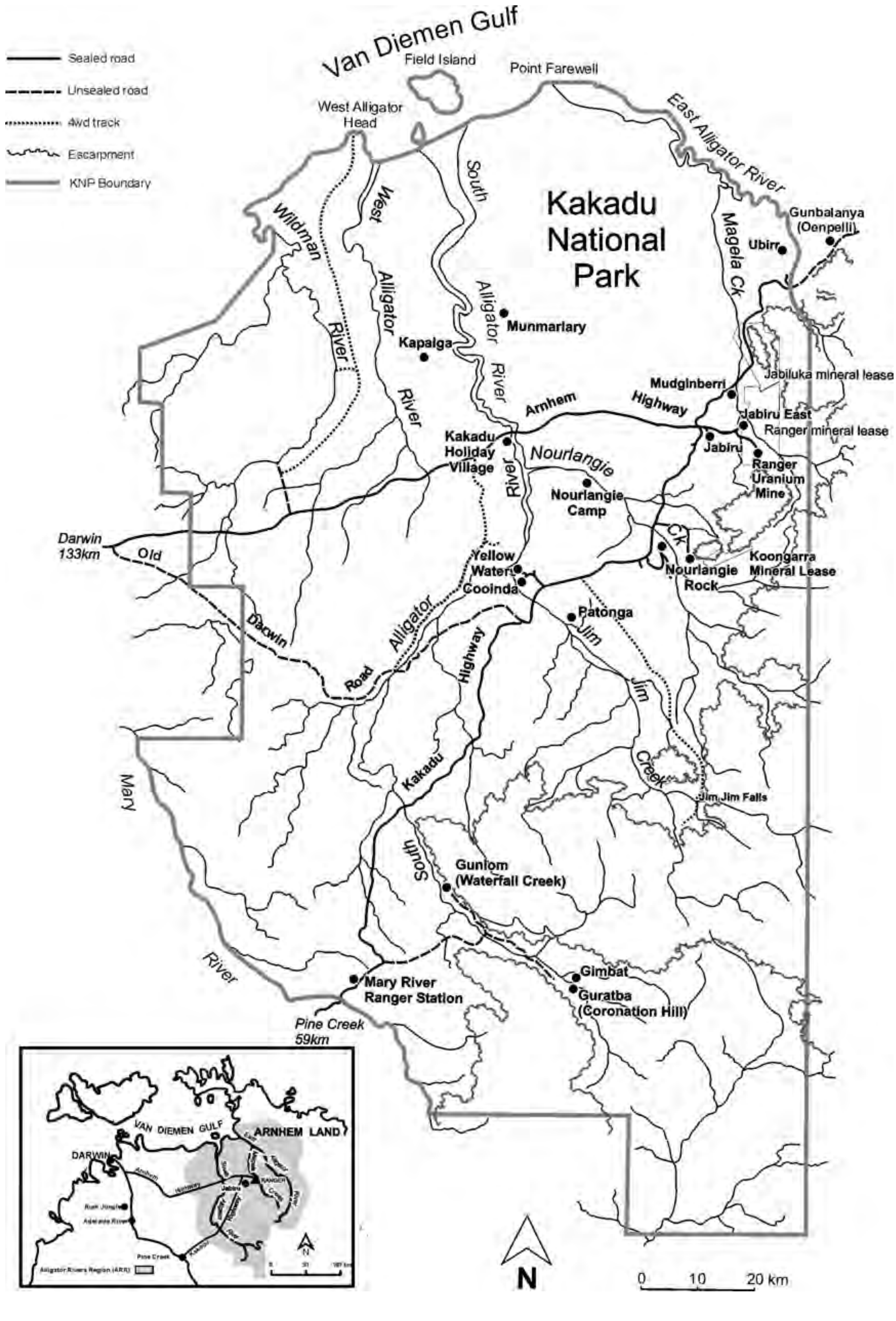

Figure 1 Location diagram for the Alligator Rivers Region

John McDouall Stuart's enthusiastic report of his explorations along the Mary River in 1862 prompted the colonial government of South Australia to seek responsibility for the Northern Territory, which had previously been administered by the colonial government of New South Wales. This granted, a settlement was established at Escape Cliffs in 1864, but was abandoned in 1867 (Reid 1990). At this time explorer John McKinlay attempted to reach the Liverpool and Roper Rivers, but made it only to the East Alligator before the Wet season defeated him and he was forced to return to Escape Cliffs, using horse hides for a raft (McKinlay 1866). His account of an attack by Aborigines is corroborated by Aboriginal oral tradition from Gunbalanya, which recounts spear throwing during a hostile encounter with Europeans (Carroll 1996).

In 1884 Captain Carrington explored the coastal rivers of the Top End, including Field Island at the mouth of the South Alligator River (Carrington 1890).

John Lewis, who took a lease on Cobourg Peninsula and formed the Cobourg Cattle Company, travelled twice through the Alligator Rivers Region in the 1870s. He recorded the presence of Timor ponies, Sourabaya and shorthorn cattle, and buffalo at the abandoned Port Essington settlement on Cobourg Peninsula (Lewis 1922).

3.3 Settlement history

It is believed that the first confirmed contact between Aboriginal people of the Region and outsiders occurred in the early 1700s, and possibly even earlier, when Macassan fishermen set up trepang harvesting camps on the coast (Senate Standing Committee 1988). Macassan camps were usually on the seashore, close to good drinking water and mangroves, which were used for drying and smoking the trepang (Cole 1973). There was intense Macassan-Aboriginal interaction during this period (Gillespie unpub).

British ownership of the Region was asserted in the 1800s with the establishment of administration settlements such as Fort Dundas (1824–29), Raffles Bay (1827–29) and Port Essington (1838–49). These military settlements were all short-lived, but they played a major role in shaping future land use of the area, as they resulted in the release of Banteng cattle, pigs, buffalo and cattle tick onto Cobourg Peninsula.

A settlement was established at Port Darwin in 1869, and administered from South Australia. Population centres grew, with the discovery of gold at Pine Creek and a subsequent influx of Chinese labour to the Northern Territory in the 1880s. A railway was built from Darwin to Pine Creek and gold mining expanded into the Alligator Rivers Region.

Buffalo shooters arrived as early as 1873 to exploit the large herds of feral buffalo on Cobourg Peninsula (Carroll 1996), and later on the floodplains of the Mary and Alligator Rivers. Attempts to establish cattle stocks at this time failed (Christian 1973), but there was greater success for pastoralists from the 1930s onwards.

In late-1950s to early-1960s the buffalo hide industry collapsed and the meat industry gained momentum, becoming more centralised and requiring greater infrastructure. Permanent meat processing structures were established, land cleared and roads constructed or improved.

Mineral exploration yielded results with the discovery of uranium in the upper South Alligator River catchment in 1953, and further afield in 1970. Gold mining had continued with intermittent success, and a new road built to Mt Bundy (iron ore) mine improved access and infrastructure for further ventures. This road was extended to become the Arnhem Highway. A proposal to mine the Ranger uranium deposit focused attention on the Northern Territory, sparking a national debate on the uranium issue, with concerns about the vast natural beauty and cultural significance of the Alligator Rivers Region (Finlayson & von Oertzen 1996a). The township of Jabiru now provides housing and services to much of the Alligator Rivers Region, having been established in 1982 to service the uranium mines planned for the Ranger, Jabiluka and Koongarra leases.

Gunbalanya township in Arnhem Land, has expanded into a town with a largely Aboriginal population. It is administered by a local community council that provides services for the township and nearby outstations.

3.3 Administration history

Following European settlement of Australia, the Northern Territory was administered from New South Wales. In the early 1860s the South Australian Government sought responsibility for the Northern Territory, and the British Government agreed to the request. The South Australian Government administered the Northern Territory until 1911, when the Australian Commonwealth Government assumed control and established the Department of the Northern Territory. Powers of self-government were awarded to the Northern Territory in 1978, although the Commonwealth retained management of Kakadu and Uluru-Kata Tjuta National Parks and control over uranium mining and Aboriginal land rights under a joint management arrangement with the traditional Aboriginal landowners. Parks Australia North, an agency of Environment Australia, currently administers Kakadu. Since 1981 an elected local council has administered the township of Jabiru, with one member appointed by the operator of the Ranger uranium mine.

4 Major land uses

4.1 Pastoral

Pastoral leases were unsuccessful in the late 1800s as redwater disease from cattle tick severely affected cattle stocks. Cattle ticks were still abundant in the Coronation Hill area in 1979, particularly during the Dry season (Story 1979).

Buffalo hunting began in the Region in the 1880s, and continued with some interruption until the 1960s (Christian 1973). Thousands of buffalo grazed the plains of the Alligator Rivers. Paddy Cahill arrived in the Alligator Rivers Region in 1894 and commenced a buffalo shooting operation, involving Aboriginal labour as the industry grew (Chaloupka 1993). Cahill moved to Oenpelli and started a dairy farm and garden in 1906. This property later became an agriculture experimental station, a mission station and later the township of Oenpelli, now known as Gunbalanya.

In 1933 a grazing licence was issued for Kapalga, then a buffalo hunter's camp (Cole 1988). An assortment of shacks and humpies were built and tobacco grown. Over 1000 buffalo could be shot in a Dry season, from horseback. The hides were washed and salted, stacked on top of one another for five days and then hung on racks. At the end of the season the hides were taken by dray and later by truck to a river jetty for shipment to Darwin. There was a bush timber jetty on the South Alligator, about a mile from Kapalga (Cole 1988).

Gundjai cattle station was established near Yemelba (Imarlkba) gold mine in the Barramundi Hills in the early 1950s, to exploit the populations of feral cattle and buffalo. It operated with Aboriginal participation but closed in the mid to late 1960s (Gillespie unpub).

A renewed interest in buffalo for pet meat and human consumption in the 1960s led to the issuing of the Mudginberri and Munmarlary pastoral leases in the Alligator Rivers Region in

1969 (Christian 1973). The Munmarlary lease for 1010 km^2 was issued for the exploitation of feral buffalo meat, although buffalo shooters had occupied Munmarlary since the late 1940s. Buffalo were hunted on the eastern side of the South Alligator River, and the hides were salted at Munmarlary billabong. Station buildings, an airstrip and an abattoir were built. Later a causeway was built on the floodplain for all-weather access. The Mudginberri lease was 1106 km^2 and an export standard abattoir was built on the property to process buffalo meat from Mudginberri and Munmarlary stations (Finlayson & von Oertzen 1996b). A large number of Aboriginal people were regularly employed on the stations and at the abattoir (Sidgwick 1962, Gillespie 1988).

Leases were issued for Goodparla and Gimbat stations in 1961 and 1962 respectively. Both stations supplied meat to Pine Creek and the mining settlements in the South Alligator River valley. Neither station was a profitable cattle enterprise (Story 1979). Improved pasture schemes aimed to provide better stock nutrition, but were short-lived and the introduced pasture species, such as Para grass (*Brachiaria mutica*), have since become weeds in Kakadu National Park (Brock & Cowie 1992, Finlayson & von Oertzen 1996b).

The Federal Government resumed the Munmarlary and Mudginberri pastoral leases in 1978 and fully incorporated them into Kakadu National Park by 1984. Goodparla and Gimbat stations were resumed and incorporated into Stage III of Kakadu National Park in 1987, in order to protect the South Alligator River catchment. At that time there were an estimated 2000 buffaloes, 1000 cattle, 200–300 brumbies and an inestimable number of pigs in the area. These animals were assumed to be the cause of accelerated sheet and gully erosion observed during CSIRO surveys of the area (Story 1973, 1979, Graetz 1989).

Buffalo mustering continued in Kakadu under the Brucellosis and Tuberculosis Eradication Campaign (BTEC) until 1988. Buffalo catching became part of a systematic buffalo eradication program in Kakadu National Park and the animals were processed at the Mudginberri abattoir. Buffalo in more inaccessible terrain were shot from helicopters. This program was highly successful at reducing their numbers, for example 16 000 buffalo were shot in 3–4 years in the Woolwonga area, reducing their population to less than 2000 in the 1980s (Lucas & Russell-Smith 1993). A total of 50 000 buffalo were removed from Stages 1 and 2 of the Park since 1979, and almost 25 000 from Stage 3 since its inclusion into Kakadu. However, there continues to be stray movement of buffalo into the Park from Arnhem Land (Finlayson & von Oertzen 1996b).

The Mudginberri abattoir closed in 1988, heralding the end of an era of pastoral leases and a buffalo industry in the Region (Finlayson & von Oertzen 1996b). Ten years later, however, local Aboriginal people have proposed the establishment of buffalo farms to provide meat for the local population (Kakadu Board of Management & ANCA 1996). There is currently one farm of about 600 head of domesticated buffalo on the South Alligator floodplain, managed by the Gagadju Association (Finlayson & von Oertzen 1996b).

4.2 Mining

Gold was discovered at Pine Creek in 1880 and serviced by a railway line from Darwin. Chinese labour dominated the mines and railway, with the emergence of a number of influential Chinese merchants in the goldfields (Jones 1987). Gold mining activity soon expanded into the Alligator Rivers Region. Small-scale mining ventures by the Chinese involved local Aboriginal men and women.

The Yemelba (Imarlkba) or Barramundi mine in the Barramundi Hills was discovered and worked by Chinese in the late 1800s with the assistance of local Aboriginal people. Later it was actively worked during a gold search in the mid-1930s. The Arnhemland Gold Development Company was floated in Sydney in 1933 to exploit the alleged gold deposits, and exploration was carried out during the next two years. There is strong archival evidence, however, that fraud was involved and the mine had been 'salted' with gold purchased elsewhere (Gillespie 1988, 'Arnhem Land Gold' in *The Bulletin* 1935). After the Arnhemland Gold Development Company collapsed in 1935, the mine's alluvial deposits were worked with moderate success by others until 1941. The Yemelba mine, like many others in the Region, now lies abandoned (Commonwealth of Australia, Dept Housing & Construction 1986).

Uranium was discovered at El Sherana in the upper South Alligator catchment in 1953. This triggered an extensive search for uranium in the Region. Mining at Coronation Hill alongside the South Alligator River and at Sliesbeck on the headwaters of the Katherine River began, but succumbed to adverse market pressures and ceased by 1964 (Forrest 1987).

In 1970 Queensland Mines announced a rich uranium deposit at Nabarlek in the Arnhem Land Aboriginal Reserve. Mineral prospecting licences were issued for the entire Alligator Rivers Region (Christian 1973). The large Koongarra and Ranger uranium deposits were also discovered in 1970, followed by Jabiluka in late 1971. National publication focused on the Region, resulting in the Ranger Uranium Environmental Inquiry (Fox et al 1977). Nabarlek ore was mined in 1979 and stockpiled, to be processed between 1980 and 1988. These mine operations have since closed and the site is being rehabilitated. Mining and commercial production of the uranium concentrate, yellowcake, commenced at Ranger in 1981, where mining of a second ore-body is now underway. Until 1996 the number of uranium mines in Australia was limited to three by Commonwealth Government policy, but the abolishment of this policy paved the way for uranium mining to become a more dominant land use in the Region, with proposed development of the Jabiluka and Koongarra sites. Koongarra remains undeveloped to date, and subject to further environmental investigations and negotiations with the traditional Aboriginal landowners approval has been given by the Commonwealth Government for an underground mine at Jabiluka. Some infrastructure has been established at the Jabiluka site, in preparation for mining.

4.3 Logging

There were large stands of cypress pines (*Callitris intratropica*) and paperbarks (*Melaleuca leucadendra*) at Nourlangie Camp up to the 1950s. The plentiful timber had been exploited by the Chinese in the late 1800s, when timber was dragged to the mouth of Nourlangie Creek by sixteen-horse teams and towed on scows to Darwin (Stewart 1969). The Arnhem Land Timber Company operated at Nourlangie Camp in the early 1950s and logged both *Callitris intratropica* and *Melaleuca leucadendra* by axe. Cypress timber was transported to Darwin for use as panelling and floorboards and used in the mines at Gimbat, Moline and Katherine (Lucas & Russell-Smith 1993). In 1959, the facilities were sold to Allan Stewart to be run as a safari camp (Stewart 1969). Now part of Kakadu National Park, fire breaks have been created around the cypress stands at Nourlangie Camp and regeneration is occurring (Lucas & Russell-Smith 1993).

4.4 Fishing

Commercial fishing has taken place in river estuaries of Kakadu since the 1950s but has since ceased. In the period 1981–1985, the commercial barramundi catch ranged from 57 to 145 tonnes, with recreational fishing within the Park estimated to catch similar quantities. Recreational fishing continues, with barramundi the principal target while large numbers of threadfin salmon, jew fish and miscellaneous reef-fish are caught offshore (Miles 1999). A number of billabongs and rivers in the Region are popular fishing spots and have been developed, with the addition of campgrounds, parking areas and boat ramps to assist access. Fish-cleaning areas have been established to try to minimise the threat of crocodiles to anglers, but fishing is not actively promoted (Miles 1999).

4.5 Tourism

Prior to the declaration of Kakadu National Park, the Alligator Rivers area was a base for several safari operations. In the late 1950s and early 1960s visitors were measured only in the hundreds, the majority being Darwin residents who made the four-wheel drive trip to the Region to hunt and fish. Alan Stewart established Nourlangie Camp in 1960, Tom and Judy Opitz built Jim Jim store, Frank Muir ran Muirella Park safari camp and the McGregor brothers operated a camp at Patonga (McDonald 1989). Buffalo, pigs, crocodiles, kangaroos, barramundi, geese and numerous other bird species were hunted (Stewart 1969).

Construction of the Arnhem Highway by the Commonwealth Government to assist mining ventures in the area also served to increase accessibility of the area to tourists. It paved the way for the emergence of tourism as a dominant land use of the Region. Completion of the highway in 1974 coincided with increased public exposure of the Region, triggered by the release of the Alligator Rivers Region Environmental Fact Finding Study, a comprehensive report on the area's natural, mineral and cultural assets (Christian 1973, Miles 1999). Following the proclamation of Stage 1 of Kakadu National Park in 1979, visitor numbers soared to 20 000. In 1984 Stage 2 was added to the Park and 75 000 people visited Kakadu. This increased to 220 000 in 1988. Since then visitor numbers have been much the same. However, the tourist profile has changed, with more people now touring Kakadu in commercial groups rather than travelling independently (Miles 1999). With the accompanying demand for services and improved visitor access in Kakadu, tourism is in itself a threat to the environment and a challenge for land managers in the Region (McDonald 1989). The balance between tourism and the indigenous use of the Kakadu landscape, particularly concerning wetlands, is also a constant management challenge for Parks Australia (Miles 1999).

4.6 Aboriginal Reserves

The Oenpelli area was declared the Western Arnhem Land Aboriginal Reserve in 1920, and included in the much larger Arnhem Land Aboriginal Reserve in 1931 (Finlayson & von Oertzen 1996b). JW Bleakley, the Chief Protector of Aboriginals in Queensland, prepared a Commonwealth Government report and recommended that an Arnhem Land reserve be established:

> There should be no obstacle to this, as the country is very poor, no one requires it, and those who previously have taken some of it up have abandoned it (Bleakley 1929, *The Aboriginals and half-castes of Central Australia and north Australia*. Government Printer, Melbourne, cited in Crough 1992, pp20–21).

The Woolwonga Aboriginal Reserve in the Nourlangie Creek catchment was declared in 1936 and its boundaries revised in 1968 (Christian 1973). Entry to these areas was usually restricted to Aboriginal people, enabling them to maintain their ceremonial culture and live a reasonably traditional lifestyle if they chose. However, the Aboriginal population in the Alligator Rivers Region still declined dramatically, due to disease and other adverse contact with Europeans and Chinese (Gillespie unpub, Carroll 1996). The Woolwonga Aboriginal Reserve was incorporated into Stage 1 of Kakadu National Park.

4.7 Conservation reserves

In 1964, the Woolwonga Wildlife Reserve was established with similar boundaries to that of the Woolwonga Aboriginal Reserve (Christian 1973). The following year, the Northern Territory Reserve Board proposed the establishment of a national park in the Alligator Rivers Region with an area of about 6410 km^2. Amended proposals followed, and in 1969 the Minister for the Interior approved in principle the reservation of 2590 km^2 for a national park adjacent to Arnhem Land.

Two areas in the vicinity of Deaf Adder Gorge (233 km^2) and Jim Jim Falls (100 km^2) were reserved from mining in 1971, and in 1972 much of the proposed national park area (3290 km^2) was declared the Alligator Rivers Wildlife Sanctuary (Christian & Aldrick 1977, Finlayson & von Oertzen 1996b). It was administered by the Forestry, Fisheries, Wildlife, Environment and National Parks Branch of the Federal Department of the Northern Territory (G Miles pers comm 1997). The Alligator Rivers Wildlife Sanctuary was small when it was declared in 1972 and consistent with the boundary later established for Stage 1 of Kakadu National Park (Miles 1999).

In 1972 the Aboriginal population of the Region was very low, and the era of buffalo shooting and pastoral stations drawing to a close. The safari camp at Patonga was handed over to the Federal Department of the Northern Territory for use as an Alligator Rivers Wildlife Sanctuary ranger station (L Barnett pers com 1997).

A scenic reserve of 235 hectares was established in 1971 at Waterfall Creek, a landform now within Kakadu National Park and known as Gunlom.

In 1974 the 4.5 hectare Christmas Creek Cave Paintings Reserve was proclaimed in the South Alligator valley. These paintings were accessed via a precipitous mining track on the southern side of the South Alligator River. The track has long been closed for safety reasons, but the Jawoyn landowners are considering re-opening the site to the public (G Miles pers com).

In 1973 the then Prime Minister announced there would be a national park named Kakadu, and the recommendations of the Ranger Uranium Environmental Inquiry in 1975 reinforced this decision. Stage 1 of Kakadu National Park (6144 km^2) was proclaimed in 1979, followed by Stage 2 (6929 km^2) in 1984. Stage 3 of the Park (4479 km^2) contained a Conservation Zone area within its boundaries when it was declared in 1987. The mysteriously named Conservation Zone was open to mineral exploration but proposed resumption of mining activities at Coronation Hill did not go ahead after long and heated national debate. The Conservation Zone eventually became part of Kakadu Stage 3 in mid 1991, bringing the total Park area to 1 975 000 hectares (Senate Standing Committee 1988, Finlayson & von Oertzen 1996b).

Stage 1 of Kakadu was the first Australian site to obtain World Heritage listing under the Convention Concerning the Protection of the World Cultural and Natural Heritage in 1981, and by 1992 all three stages of the Park had been included under the Convention. In 1980 Stage 1 became a designated site under the Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat. Stage 2 was listed under Ramsar in 1984 and now all Kakadu’s wetlands have Ramsar status. Such recognition of the high value of the Park carries with it an obligation to conserve and protect both its cultural and natural heritage (Finlayson & von Oertzen 1996b), a challenging task which requires the balancing of conservation, indigenous, tourism and multiple land use philosophies (Press & Wellings 1989). Kakadu National Park is jointly managed by Parks Australia North and a Park Board of Management, which has an Aboriginal majority. The Board represents traditional owners, Parks Australia North, tourism and research (Miles 1999).

4.8 Population centres

The substantial Chinese population in Darwin and Pine Creek up until World War I impacted upon the Aboriginal culture of the Mary and Alligator Rivers Region, with intensive interaction between the two, bringing dramatic cultural change for Aboriginal people near settlements (Gillespie unpub). In World War II Australian Army patrols in the Region brought Aboriginal people together into control camps, such as Cullen River near Pine Creek.

In the early 1970s areas were allocated for road construction, in particular the Arnhem Highway. Several developed sites existed, such as a hotel-motel at Cooinda, safari camps at Patonga, Nourlangie Camp, Jim Jim and Muirella Park, and the mine leases in the El Sherana area on the upper South Alligator River (Christian 1973). After completion of the Arnhem Highway in 1974, a roadside hotel was established at South Alligator (G Miles pers com 1997).

4.8.1 Jabiru

The planning of a regional township began in the 1970s in anticipation of developments arising from pastoral, mining and tourism. The townsite of Jabiru was chosen in the late 1970s, but people first occupied a camp near Georgetown billabong and then a township at Jabiru East, close to Ranger Mine. The town was moved to its present site in 1982 (Jabiru Area School 1984). The population at the 1996 census was 1455, with over 700 residents in surrounding settlements and tourist facilities (Australian Bureau of Statistics pers com 1997). The population is becoming more diverse as industries other than mining expand and Aboriginal organisations establish ventures in the area. It now supports various non-mining related organisations, the tourism industry in Kakadu National Park and small settlements of Park rangers and Aboriginal people. As a leased area (13 km^2) within Kakadu, the townsite is subject to regulations concerning the introduction of exotic animal and plant species, resource and land use. The Jabiru Town Council incorporates the Kakadu Plan of Management into its by-laws (D Norton pers com 1997).

4.8.2 Gunbalanya

Gunbalanya (Oenpelli) in Arnhem Land currently has a population of 800–900 people and supports the smaller groups of Aboriginal people living at outstation communities via gravel roads and an airfield (Finlayson & von Oertzen 1996b). A community council administers the township. There is a large freshwater billabong nearby, and three hills, Inyalak, Arrguluk and Nimbabirr overlook the town, the whole area being known as Gunbalanya in Kunwinjku (Cole 1980).

4.9 Scientific research

Kapalga, an area of 670 sq. km of floodplain and upland ecosystems within Kakadu National Park, was set aside as a research station in 1976 (CSIRO 1990). The CSIRO Division of Wildlife and Ecology held Kapalga as a ‘permissive tenancy’ and carried out research into the ecology and management of ecosystems in the Wet-Dry tropics for 15 years. Experiments were conducted on floodplain, woodland and forest habitat within the Kapalga area. There were three phases of research at Kapalga, including long-term landscape-scale experiments on the impacts of buffalo and fire. In 1984 Kapalga was incorporated into Kakadu National Park as part of Stage 2, which was later added to the World Heritage List (CSIRO 1990). CSIRO has since withdrawn from the station and it is now managed by Parks Australia North.

The Environmental Research Institute of the Supervising Scientist has a laboratory complex near the Jabiru airstrip on the Ranger mining lease. The institute was established in 1978 and variously known as the Office of the Supervising Scientist and the Alligator Rivers Region

Research Institute. Until 1994 the institutes activities were strictly confined to research into the possible environment effects of uranium mining, particularly related to the Ranger mine. It now has a wetland ecology and conservation research program to complement the mining related environmental research.

5 Environmental change

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 investigations and research. Historical records and diaries can also shed light upon the nature of the landscape prior to extensive non-Aboriginal land use in the Region, assisting researchers and land managers to differentiate between natural and artificial change, and determine management priorities.

5.1 Impact of feral buffalo

Lucas and Russell-Smith (1993) recorded Aboriginal perceptions of environmental change on the South Alligator River floodplain. The elderly people were able to describe the landscape prior to widespread buffalo damage, and relate this to changes that have occurred since the buffalo were removed. In some billabongs and waterways it appears that the habitat is returning to its pre-buffalo state, ie increased vegetation cover. This corresponds with observations of barrumbarrum (*Scleria poaeformis*) regenerating in paddocks without buffalo, and around floodplains since a reduction in buffalo numbers (Lucas & Russell-Smith 1993, D Lindner pers com 1997).

Aboriginal people associate buffalo with dramatic environmental change at Big Banyan Billabong. Prior to 1953 there was a large billabong with *Barringtonia acutangula*, *Melaleuca viridiflora*, *Pandanus aquaticus* and *Bambusa arnhemica* growing around the banks, and lilies and *Hymenachne acutigluma* in the water. Mullet, saratoga, file snakes, saltwater crocodiles and turtles inhabited the billabong. A large buffalo population in the area is blamed for causing saltwater intrusion that killed the trees and ultimately drastically changed the nature of the billabong. However, within a few years of depletion of buffalo numbers, the vegetation and some of the animal populations recovered (Lucas & Russell-Smith 1993).

Silting of a billabong at Murrewa through bank erosion by buffalo has resulted in the disappearance of this waterbody altogether (D Lindner pers com 1997).

The legume *Aeschynomene aspera* once grew in abundance on the floodplains. It was depleted by the large numbers of buffalo in the area, and has not recovered (Lucas & Russell-Smith 1993). Buffalo also appear to have inhibited the growth of *Cathormion umbellatum* and *Hymenachne acutigluma* which are now encroaching on floodplains and billabongs again (Lucas & Russell-Smith 1993, Corbett et al 1996). Some Aboriginal people view this as a problem, believing that excess *Hymenachne* will prevent the breeding of file snakes, fish and birds, but several of the older women disagree, noting that the vegetation is returning to pre-buffalo distributions (Lucas & Russell-Smith 1993).

Trampling, grazing and wallowing activity of buffalo and rooting by pigs in the wetlands and forest margins are believed to indirectly influence reptile and amphibian species distributions (Friend & Cellier 1990), favouring some species and negatively impacting upon others. Long neck turtles (*Chelodina rugosa*) were not found by Aboriginal people on the Bulkinj floodpains while buffalo compacted the mud, but since the buffalo were removed, turtles have returned, possibly due to the mud returning to a more aerated state (Lucas & Russell-Smith 1993).

Many *Melaleuca leucadendra* trees died when salt water intruded into fresh water swamps disturbed by buffalo. A dam was made at Indarrgu in 1981, to try to reverse this process. Salt water grasses were planted to stabilise the dam bank and the channel. Young *Melaleuca* trees and *Scleria poaeformis* are regenerating, but regeneration of *Phragmites karka* has been slow despite efforts to increase its distribution on the lagoon side of the dam (Lucas & Russell-Smith 1993).

At Maguk (Barramundi Falls), the weed *Hyptis suaveolens* is thought to have been transported there by buffalo (Lucas & Russell-Smith 1993). Feral animal species such as pigs and buffalo have an apparent role in promoting the invasion of weed species in the Park, as disturbed areas often have more weeds present than natural areas. Wetlands and their margins appear to be particularly susceptible to invasion by weeds when disturbed by buffalo or pigs (Cowie & Werner 1993).

5.2 Impact of feral pigs

Pig damage is most conspicuous in the swamp areas, where trampling and rooting activity is concentrated. Pigs feed on a varied diet, including water lillies, yams, long neck turtles and water beetles (Lucas & Russell-Smith 1993). Damage to the swamps and creeks leaves areas more susceptible to invasion by weeds (Cowie & Werner 1993).

Culling of feral pigs in Kakadu is on an opportunistic basis only, due to the huge costs and the logistical problems associated with their effective eradication.

5.3 Introduced plants

Macassan trepang gatherers who visited the coastline of the Region left tamarind (*Tamarindus indica*) seeds on the beaches, which have since grown into large, conspicuous trees (Chaloupka pers com 1997, Cole 1973). Not considered a problem species, the tamarinds are one of the most obvious Macassan influences in the landscape itself, notwithstanding the social and cultural changes that occurred.

There has been a significant increase in the number of alien plants recorded in the Alligator Rivers Region since 1973, from 30 species to 71 species in 1986 (Cowie & Finlayson 1986). This increase coincides with the expansion of settlements, roads and tourism in Kakadu National Park. Humans and feral animals have an apparent role in promoting the invasion of weed species in the Park. Wetlands and their margins are particularly susceptible to invasion by weeds when disturbed by buffalo or pigs (Cowie & Werner 1993). Change in the mobility of Aboriginal people, who are now using four-wheel drive vehicles, may facilitate the spread of weeds between hunting grounds (S Lord pers com 1997). Park management has long been concerned about recreational fishing and associated vehicle movements as a source of *Salvinia molesta* contamination, occasionally establishing vehicle checkpoints on the major roadways to help slow its spread and increase public awareness of the issue. This is part of an integrated control program for salvinia (Storrs & Julien 1996). Park employees regularly patrol Kakadu to locate and eradicate *Mimosa pigra* infestations. Para grass (*Brachiaria mutica*) is emerging as a major threat on the floodplains (Cook et al 1996, Storrs & Finlayson 1997, Finlayson et al 1998).

Alien plant species at settlements within Kakadu National Park were extensively reviewed recently and a number of recommendations made for those weeds requiring urgent removal (Brock & Cowie 1992).

5.4 Impact of tourism

Prior to the existence of Kakadu National Park, impact of tourism on the fauna of the Region's wetlands was direct, involving safari camps and the hunting of both native and feral species (Stewart 1969). The overall environmental damage, however, is debatable and there is little scientific evidence to allow accurate assessment. Tourist numbers were relatively low and the wetlands in particular are highly dynamic systems. More recently, visitor numbers to the Region have increased (Miles 1999). Increased visitation and upgrading of services in an area to accommodate more tourists can lead to greater environmental impact. Tours and individuals then wish to visit other less-developed areas, thereby extending the area potentially impacted by tourists. In Kakadu there is the inevitable 'nature of the development versus preservation trade-off' (Knapman et al 1991). Research is carried out on specific issues to assist the Park managers to make decisions and assess environmental impacts. This is done on a consultancy basis, as the case for recreational angling (Duff 1989), bank erosion and tour boats (Cullen & Taylor 1988, Braithwaite et al 1996), sunscreen and insect repellants in waterholes (Rippon et al 1994), and road-creek crossings (Stowar et al 1996). However, there remains the need for research to investigate the complex challenge of the positive monetary values of tourism and the negatives of disturbance to the environment and potential decline in Park preservation worth, within the context of Kakadu's unique natural and cultural heritage (Knapman et al 1991).

6 Conclusion

Post-European settlement land use of the Region has been dominated by exploitative use of minerals and animals. Buffalo and crocodile shooters arrived in the 1880s and this industry continued until the 1960s. Pastoral and gold mining ventures have met with varying degrees of success since the 1880s and continue today, although with vastly altered techniques. Uranium mining has been an important land use within the Alligator Rivers catchments, acting as a catalyst for other industries through its provision of basic infrastructure. Conservation and tourism interests in the Region have increased rapidly since the 1960s and play a dominant role in current land management and decision-making, along with Aboriginal people who still make semi-traditional use of the land. Significant proportions of visitors to the Region are recreational fishermen. Population settlements are both natural results of most of the above activities and a source of environmental impact in their own right.

Environmental impacts have occurred in the Region as a result of past and current land use, and change such as the introduction of animal and plant species. There is a need for further assessment into the nature of the impacts and implications for management, particularly associated with the mining and fast-expanding tourism industries. Changes in the floodplains and streams should be placed in the context of broadscale coastal change as postulated by Bayliss et al (1997). The process of identifying the reasons for and extent of land degradation of the coastal Region, where land use has been most intense, will rely on further literature research and oral interviews. The latter requires urgent attention. All information gathered requires collation and storage in standardised formats (Finlayson & Bayliss 1997). Similarly, a metadatabase is required to demonstrate relationships between the various data storage files.

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Chapter 4 Collation of baseline information: The coastal plain

4.1 Introduction

Environment changes on the coastal plains of the Alligator Rivers Region are triggered by broad scale processes. They are apparent as localised changes in the distribution and composition of mangals, headward extension of tidal creeks, and salinisation of former freshwater areas. These have been considered in the monitoring program. They are briefly outlined below.

Mangrove levees define the margins of the ocean coast and tidal reaches of the rivers. Where they have been destroyed the coast is susceptible to retreat and the river banks to destabilisation and erosion (Woodroffe & Mulrennan 1993, Cobb 1997). Apparent physical processes of mangrove destruction are:

- shoreline retreat and erosion of the coast;
- overwash by extreme high tides and surge events;
- basal sapping by groundwater followed by the initiation of tidal streams and their expansion;
- destruction of mangroves by feral animals.

Headward expansion of tidal creeks within the Alligator Rivers Region has been reported by managers and researchers, the latter including Woodroffe et al (1991), Woodroffe and Mulrennan (1993), Cobb (1997) and Hill et al (1998). The expansion has been rapid. There has been an exponential increase in the length of tidal channels in several river systems during the past 50 years. Reasons for the increase include:

- increased tidal range through channel restructuring caused by oceanographic and fluvial processes;
- linkage of fluvial and tidal systems;
- vegetation effects on channel salinity structure;
- residual effects of buffalo swim channels.

Away from the ocean coast, although not always the tidal creeks, salinisation of broad basins has resulted in die back of freshwater vegetation and its replacement with salt tolerant species. In many instances the changes appear to be localised. They may be due to several processes, including any one or some combination of:

- ponding and evaporation;
- basin consolidation and compaction;
- tidal deposition;
- fluvial infilling;
- groundwater percolation through vertical and lateral flows.

The three areas of change, shorelines, tidal creeks and low lying basins, offer a wide range of potential applications for the monitoring program. Not all of these can be addressed by management agencies in the Region as part of their areas of responsibility. Hence there is a need for cooperative investigation of local problems. Such investigation is necessarily adventitious at present and dependent on the availability of resources to undertake particular tasks. Nevertheless, some local monitoring projects have commenced and progress with them is reported below.

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Paper 7 Coastal change and shoreline movement in the Alligator Rivers Region

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Abstract

Vulnerability of the Alligator Rivers Region to climate change has been identified. In response, the Environmental Research Institute of the Supervising Scientist has established a coastal assessment and monitoring program to evaluate the biophysical consequences to climate change. Amongst the critical sub-components of the program is evaluation of the physical change to the coast, and assessment of the historical response to climate changes. Review of the available methods of analysis has been undertaken, including a summary of the information available to complete the analysis. Photogrammetric techniques have been identified as the most appropriate method to analyse historic shoreline change.

A program for the assessment of historical shoreline change has been defined. This assessment shall provide a baseline against which future change may be assessed. A more comprehensive baseline of information requires field survey of critical locations within the Alligator Rivers Region.

Key words: Alligator Rivers Region, Kakadu National Park, coastal monitoring, shoreline movement, photogrammetry

1 Introduction

The Alligator Rivers Region (fig 1) covers an area of 28 000 km^2 and is located in the wet-dry tropics of north Australia, approximately 150 km to the east of Darwin (Finlayson & von Oertzen 1996). It encompasses the 20 000 km^2 of Kakadu National Park, which is world heritage listed for both its natural and cultural values. The Alligator Rivers Region is located to the south of van Diemen Gulf and has approximately 85 km of coastline, behind which are extensive tracts of mangroves, salt flats and freshwater swamps. Changes in shoreline position and influences of storm surge (generally associated with cyclones) along with sea level rise could impact not only on shoreline stability and mangrove communities but also on the salt flat and areas of freshwater swamp inland.

2 Aim

The following paper is a literature and method review for coastal change and shoreline movement in the Alligator Rivers Region. The vulnerability of the Alligator Rivers Region to climate change, particularly ocean level rise has been clearly identified (Bayliss et al 1997). The Environmental Research Institute of the Supervising Scientist initiated a coastal assessment and monitoring program for the Alligator Rivers Region to examine the Region's response to climate change. The following study forms part of the assessment of baseline information available for the broader program.

It is acknowledged that limited study has been undertaken to document shoreline change through the Alligator Rivers Region. However, field observations in the adjacent lower Mary River plains have indicated considerable dynamics.

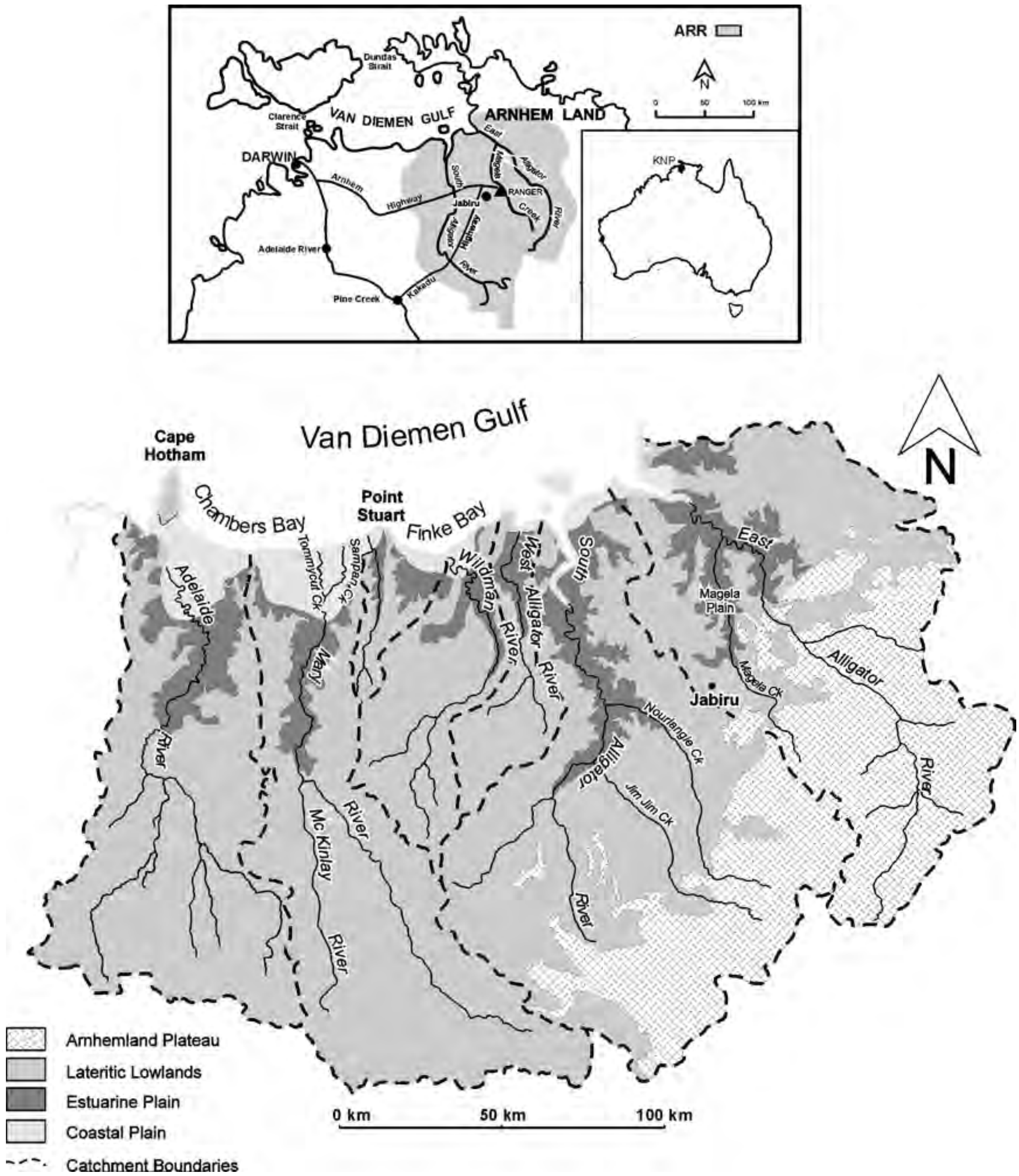

Figure1 Location diagram for the Alligator Rivers Region

Aims for the following paper are to:

- review existing literature and available shoreline change information through the Alligator Rivers Region and adjacent Regions;
- examine available methods to define the present shoreline of the Alligator Rivers Region, so as to provide a baseline with which to compare future monitoring;
- determine methods to describe historical shoreline evolutions and assess information available to accomplish these descriptions;
- determine methods to monitor and analyse current and future coastal change;
- integrate the assessment of coastal change with other related monitoring programs.

These include projects such as the status and distribution of mangrove communities, saltwater intrusions and wetland morphodynamics.

3 Historical coastal change

Climatic and sea level changes are a well documented process, with well established methods of identification, such as stratigraphy and pollen analysis. Physical and ecologic effects of past changes of sea level and climate are recorded in nearshore, coastal and estuarine sedimentary deposits and also in coral reefs (Chappell et al 1996). However, sea level has been relatively stable over the last 6000 years (Woodroffe & Mulrennan 1993, Chappell et al 1996). Given the relative stability of sea level in recent times it is of concern that considerable and rapid changes in the position and nature of the shoreline of the Lower Mary River Coastal Plains have been detected from aerial photographs over the last 50 years as described by Knighton et al (1992) and Woodroffe and Mulrennan (1993). The Lower Mary River Plains are adjacent to Kakadu National Park and both are bounded to the north by van Diemen Gulf. Field observations in the vicinity of the Mary River have recorded alternating periods of erosion, deposition and relative stability. It is anticipated that similar behaviour could occur along the shoreline of the wider Region, including Kakadu National Park. This is likely to be exacerbated by climate change phenomena, particularly potential sea level rise.

Storm surges affect many areas of low-lying coastal land throughout the world. It is typically those events that have the greatest human cost that receive the most attention. For example, Bangladesh is frequently mentioned in popular media as being affected by storm induced inundation. Murty and Flather (1994) suggest that storm surges are the world's foremost natural hazard of geophysical origin and have researched extensively in the Bay of Bengal. Closer to the Alligator Rivers Region, Tang et al (1996) have developed a simple rule to estimate sea level due to the combined effects of storm surge and tide for the north Queensland coast. However, it is not known to what extent storm waves and storm surges have impacted and contributed to the southern coastline of van Diemen Gulf, particularly the lower Mary River.

Investigations of the chenier sequence at Point Stuart (on the southern coast of van Diemen Gulf, between the lower Mary River and the Alligator Rivers Region) suggest a broad record of major storm activity in the Region during the past 1500 years. Lees (1987) argued that a variation in the type of sediments comprising the cheniers, from mainly sandy to shelly sediments indicated change in their mode of development. The landward most cheniers were thought to be a result of delta switching, a change from more arid to pluvial conditions, or some combination of these. Lees (1987) pointed out that the five seaward chenier ridges appear to have formed within the past 1270 ± 100 years in response to major storm activity and shell deposition, with the most recent phase of chenier formation at approximately 300 to 700 years ago.

4 Objective

To achieve the aim of identifying changes in shoreline characteristics in the Alligator Rivers Region the following objectives would be included:

- Use vertical aerial photographs taken since the 1940s to determine areas of accretion, erosion and apparent stability along the coastline of the Alligator Rivers Region;
- If possible identify the extent of surge washover, spring tide impact and storm impact during the historical period and determine if these processes are initiating, contributing and continuing shoreline change;
- Associate the above with the colonisation and/or destruction of mangrove communities along the coastline of the Alligator Rivers Region in van Diemen Gulf (this is associated with a mangrove project with one being symptomatic of the other);
- Accurately map the coastlines and storm surge lines using the differential Global Positioning System to provide a baseline for ongoing monitoring.

5 Available methods

5.1 Mechanisms of change

Knighton et al (1992) used aerial photography comparisons to identify substantial increases in tidal creek extension, headward from the coast for the lower Mary River floodplain. Woodroffe and Mulrennan (1993) used aerial photographs to reconstruct a series of rapid changes on the coastline of the lower Mary River floodplain over the last 50 years. The analysis indicated that shoreline retreat of up to 400 m has occurred west of Tommycut Creek and over 200 m in the vicinity of Sampan Creek, with erosion rates of approximately 4 to 8 m per year. It is not known what impact storm surges might have had on increasing these erosion rates. It is anticipated that shoreline retreat has markedly contributed to saltwater intrusion into the freshwater wetlands of the coastal floodplains of the lower Mary River, through the erosion of cheniers and levees.

Estuarine reaches of the major rivers are typically the most dynamic features of the Alligator Rivers Region, due to combining variability of oceanographic and fluvial conditions. On the basis of historical observation, these areas experience seasonal and interannual change.

However, the wider coastal margin is extremely susceptible to climate change, due to a combination of low-relief, sensitive vegetation and fragile geomorphic units. This is particularly illustrated by the rapid changes occurring in the lower Mary River floodplain subsequent to breach of the chenier barrier (Knighton et al 1992, Woodroffe & Mulrennan 1993).

5.2 Photogrammetric analysis

Photogrammetric analysis of aerial photographs has been used to identify changes in coastal areas of the world. White and Tremblay (1995) compared aerial photographs from 1930 to 1980, supported by field surveys to determine changes in wetland distribution along the coast of the northern Gulf of Mexico. Two different type of land use were delineated on the photographs and transferred to base maps, digitised and then entered into a Geographic

Information System. Similar techniques of aerial photograph interpretation have been used to monitor changes in seagrass habitat in North Carolina (Ferguson et al 1993) and map increase in tidal channels in the Alligator Rivers Region (Cobb 1997).

Photogrammetric techniques are popularly recognised as the most efficient technique for assessing shoreline change. However, poor resolution in the vertical scale (if any) determines that the technique is not suitable to assess small changes in vertical scale (up to 2 m) that commonly occur as part of coastal change. Commonly, photogrammetry will identify locations in which vertical change may be occurring, but will be unable to quantify the change. A further possible advance is the development of digital scanning and image rectification systems, which would allow illustration of all geomorphic units on the coastal margin. In this manner, the shoreline change mapping and mangrove distribution mapping may be achieved simultaneously.

5.3 Surveying techniques

Standard surveying techniques enable assessment of three-dimensional changes to topography. However, these techniques are highly intensive and prohibitively expensive, particularly in such inhospitable coastlines as the Alligator Rivers Region. Development of a differential GPS system by the Environmental Research Institute of the Supervising Scientist has enabled significant cost reduction to the survey process, but it still represents a major financial cost component.

Provision of intermittent surveys, or survey coverage over critical dynamic features may be used to evaluate future change. This requires geomorphological identification of the critical dynamic features. However, it must be noted that changes observed in the lower Mary River floodplains (Knighton et al 1992) did not occur in the presence of major geomorphic features. Consequently, this technique may provide limited capacity for assessment of future changes.

5.4 Remote sensing

Historic remotely sensed imagery does not provide sufficient resolution to enable adequate assessment of coastal change on the scale of the Alligator Rivers Region coastline. As the technology is still developing, it is possible that this may provide a future method of assessing coastal change.

5.5 Historical coastal change

Assessment of historical changes to shorelines may only be undertaken using information obtained during those periods. Historical surveys are restricted to an isolated set of transects, measured as part of an investigation of mangrove distribution (Hegerl et al 1982, Good 1994). Whilst future survey of these transects is possible, they cover only a small section of the Region’s coast and will not be representative of wider changes.

The major source of information available to evaluate historic shoreline change is aerial photography of the Alligator Rivers Region. Photographic runs of the Alligator Rivers Region coastline are available for 1950, 1975, 1984 and 1991. Position fixing of the coastline should be undertaken using surveyed locations. The Environmental Research Institute of the Supervising Scientist has developed the capacity to use differential GPS systems for position fixing, and a geographic information system for the storage of spatial information such as shoreline locations.

5.6 Future coastal change

Pending development of remote sensing technology, future assessment of change may be undertaken using photogrammetric techniques, survey techniques, or a combination of the two. The most cost-effective means of achieving this are:

- using historical photogrammetry, establish critical areas in the Alligator Rivers Region;
- provide a baseline of photogrammetry and surveying. Photogrammetry should cover the entire Alligator Rivers Region, whereas surveying can be limited to critical areas.
- undertake regular photogrammetric analyses of shoreline change, say 5 yearly;
- using the photogrammetric work, identify locations of significant change. Add any new locations to the critical areas for survey.
- survey critical areas, and compare with previous surveys.

Although this system provides a good coverage of the Alligator Rivers Region, it will not readily allow determination of vulnerable areas. This would require a complete survey of the coastline as part of the baseline establishment. The cost of this exercise is considered prohibitive.

6 Proposed future studies

Work is required to establish the geographic extent and direction of shoreline movement (if any) along the coastal margins of the Alligator Rivers Region, including Kakadu National Park. This work is particularly important given the documented extent of erosion occurring in the adjacent lower Mary River floodplains. Mapping of coastal change and shoreline movement in the Alligator Rivers Region could be undertaken in collaboration with personnel at the Environmental Research Institute of the Supervising Scientist. Aerial photographs for most dates have already been purchased by the Environmental Research Institute of the Supervising Scientist.

Possible extensions to this project could include:

- Establish if software can be used to rectify historic aerial photographs taken at different dates. It might be possible to scan aerial photographs into a GIS environment and rectify from ground points that have been accurately located with the differential GPS.
- Investigate availability and cost of Landsat and spot imagery and determine its usefulness for detecting change, ie is the ground resolution sufficient to detect changes to the coastal floodplains.
- Determine from maps of coastal change areas of potential accretion or degradation where it may be possible to establish long term survey monitoring sites for storm surges and shoreline retreat. Experiment to resolve how these sites could best be maintained with ongoing monitoring.

7 Conclusions

This paper has identified previous studies of shoreline change in the Alligator Rivers Region and adjacent regions. Physical measurement of such change is restricted to the changes occurring in the vicinity of Tommycut and Sampan Creeks, and therefore may not represent the Alligator Rivers Region coastline.

Methods for the assessment and monitoring of shoreline change have been examined.

- Photogrammetry has been recognised as the most readily available technique for analysis of historical shoreline change. Possible advances through the use of digital scanning technology and manipulation using a spatial information system require further investigation.
- Provision of an adequate baseline for the assessment and monitoring of future shoreline change requires a combination of photogrammetry and field surveying. It is expected that interpretation of the photogrammetric assessment will identify critical locations within which baseline surveys are required.

Recommendations for further progress include:

1. Undertake photogrammetric mapping of the shoreline using the most recently collected photography of the Alligator Rivers Region
2. Undertake comparative photogrammetric mapping of the shoreline using the 1950, 1975 and 1984 photography
3. Identify critical locations in the Alligator Rivers Region experiencing or susceptible to significant shoreline change
4. Undertake site surveys at the nominated critical locations.

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Paper 8 Saltwater intrusion in the Alligator Rivers Region, northern Australia

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Abstract

Intrusion of saltwater into freshwater wetlands through the process of tidal-creek extension is a major coastal management problem on the low lying coastal plains that border van Diemen Gulf in northern Australia. Research reported here documents coastal changes associated with saltwater intrusion of the Alligator Rivers Region, and completes descriptions of tidal creek and mangrove growth in streams flowing into the southern waters of van Diemen Gulf. The rate, spatial extent and geomorphological character of saltwater intrusion in the Alligator Rivers Region have been determined from an interpretation of aerial photography. The progress of tidal creek extension and mangrove encroachment on rivers of the Alligator Rivers Region was reconstructed from aerial photographs for the years 1950, 1975, 1984 and 1991 at a scale of 1:100 000.

Changes in the spatial characteristics and distribution of the tidal creeks and mangroves in the Alligator Rivers Region indicate that the saltwater reach has significantly expanded along extending creek lines since 1950. Tidal creek growth has occurred though a combination of headward extension and tributary development. The most vigorous rates of extension were along the low-lying palaeochannel swamps of the South Alligator and East Alligator Rivers. Mangrove colonisation in an upstream direction has increased at an exponential rate for river systems of the Alligator Rivers Region. This is consistent with similar findings for the coast between the Adelaide and Wildman Rivers, in an area immediately adjoining the Alligator Rivers Region. It raises questions as to why erosion is localised along the southern shore of van Diemen Gulf.

Key words: estuaries, flood plains, wetland, saltwater intrusion, Kakadu National Park (Australia)

1 Introduction

Broad, low-lying coastal floodplains flank the southern shores of van Diemen Gulf in the Northern Territory of Australia (fig 1). During the past 50 years, freshwater meadows and billabongs of the floodplains have increasingly been subject to saltwater intrusion, principally through landward extension of tidal creeks. Saltwater intrusion has been especially apparent on pastoral leases in the vicinity of the Mary River (Knighton et al 1991, 1992, Woodroffe & Mulrennan 1993), and has been identified as a major coastal management problem in the wider region (Chappell 1988, Bayliss et al 1997). However, the full geographical extent of saltwater intrusion both around the shores of van Diemen Gulf and elsewhere in the wet-dry tropics of Australia, is largely unknown. Given the geomorphological variation of the floodplains across the southern shore of van Diemen Gulf, from Darwin to the Cobourg Peninsula, it is an essential task for management to extend the scope of our understanding of environmental change to include the floodplains of the Alligator Rivers Region.

1.1 Context

Evidence of recent tidal creek extensions and problems associated with intrusion of saltwater into freshwater environments, have been observed and described within the literature for a number of rivers debouching into van Diemen Gulf, including the Mary and South Alligator Rivers.

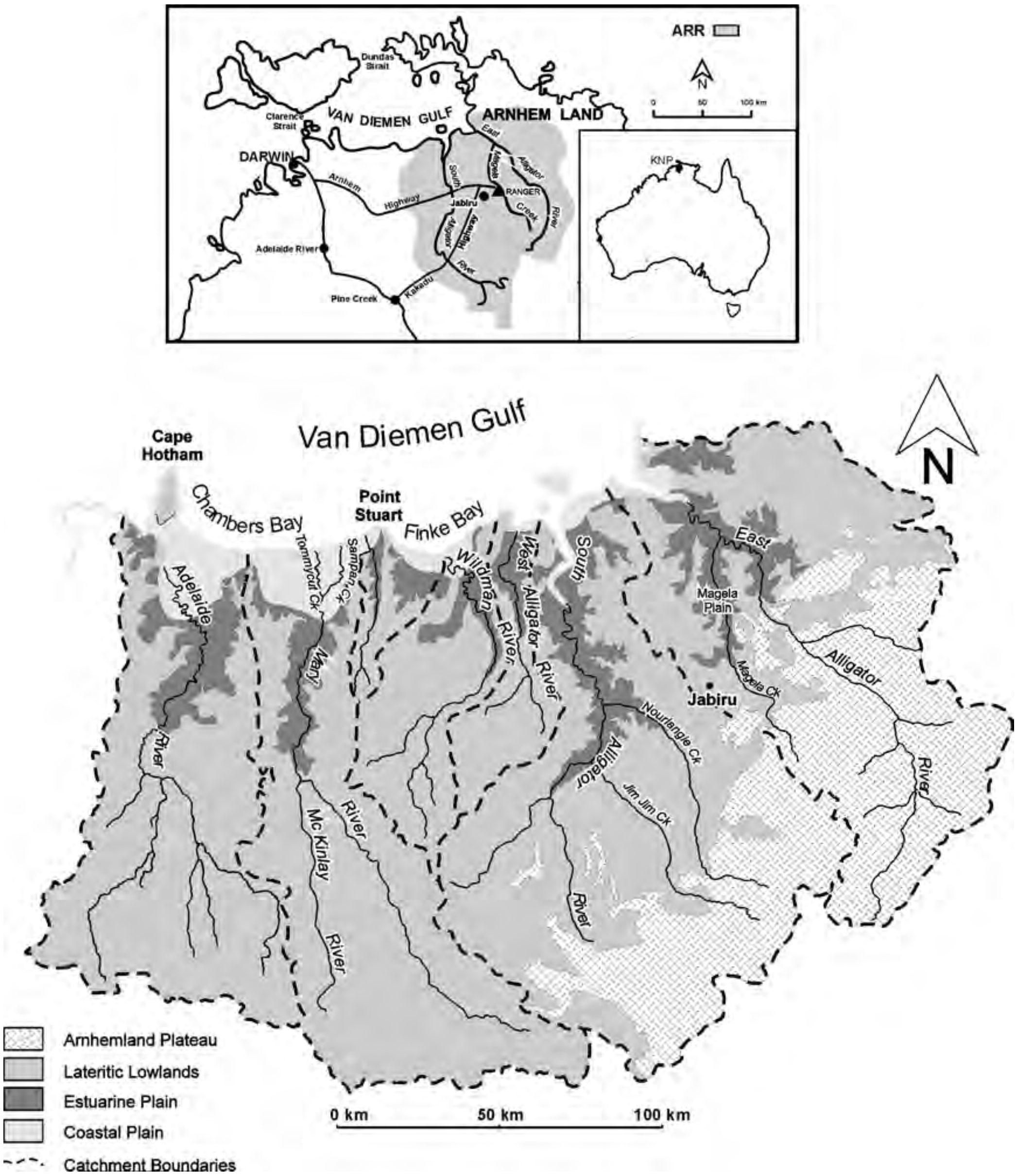

Figure 1 Location diagram for the Alligator Rivers Region

Knighton et al (1991) documented dramatic recent changes to the lower Mary River floodplains, associated with upstream expansion of the dendritic tidal creek network. Tidal creek expansion (measured by its network magnitude) has been exponential, and resulted in re-imposing a saltwater influence on the floodplains (Knighton et al 1991). Saltwater has invaded low-lying freshwater wetlands, destroying the associated vegetation and causing dieback of large areas of *Melaleuca* (paperbark) spp.

From a comparison of 1950 and 1983 aerial photography, Woodroffe et al (1986), Fogarty (1982) and O'Neil (1983) identified evidence of recent tidal creek extension and saltwater intrusion on the South Alligator River floodplains in the Alligator Rivers Region. Several tidal creeks have lengthened and extended headward towards freshwater wetlands of the floodplains. Mangroves have colonised creeklines that have become more tidally active, and into areas where there has been expansion of upper intertidal and salt mudflats due to tidal inundation. Woodroffe et al (1986) noted areas of dead *Melaleuca* spp. as evidence of saltwater intrusion into freshwater billabongs and swamps via the extending creeks.

Similar observations of *Melaleuca* spp. dieback have been observed on the Magela Creek system of the East Alligator River (Williams 1984). From comparison of aerial photographs taken in 1950 and 1976, 38% of the perennial freshwater forest, dominantly *Melaleuca* spp. which covered almost 60% of the floodplain in 1950, suffered significant loss. The changes in *Melaleuca* spp. forest density was attributed to factors other than plant succession and sediment accumulation in the swamp, although saltwater intrusion was not specifically identified as a causal effect.

1.2 Factors contributing to saltwater intrusion

Despite extensive research conducted on the Mary River floodplains and the South Alligator River, there has been no single causal explanation identified to account for the extension of tidal influences over the past 50 years. Knighton et al (1992) suggested that several factors have contributed to the floodplains' vulnerability to tidal channel extension. These factors warrant further field survey and closer examination.

Observations of the modes of tidal channel evolution on the Mary River by Knighton et al (1992), indicate that tidal channels develop though a combination of extension and widening of the main channels and tributary growth. The process of tidal channel formation reportedly begins with overbank flooding of saltwater over the floodplains during exceptionally high tides (Knighton et al 1992). Floodwaters of the Wet season may act to accentuate the process of tidal scour. Six metre spring tides in van Diemen Gulf allow the effects of tidal action to occur at the headwaters of the tidal channels, up to 105 kilometres inland (Woodroffe et al 1986). Furthermore, the macro-tidal range ensures there are bi-directional currents with high velocities within the tidal influence of channels and hence a high potential for tidal scouring (Knighton et al 1991).

Elevations of the coastal floodplains of the Mary River and the Alligator Rivers Region are less than five metres above mean sea level, and substantial regions of the coastal plains are at elevations below this (Wasson 1992, Woodroffe & Mulrennan 1993). The low gradient of the coastal and estuarine floodplains of the northern coast of van Diemen Gulf emphasises the degree to which they are vulnerable to exploitation by invading saltwater channels, or are likely to become evaporative ponds in the dry. The latter follows overbank flooding during the Wet season, or during phases of extreme spring tidal fluctuation.

A series of distinct palaeochannels are recognisable within the Alligator and Mary River Regions (Woodroffe et al 1986). These are remnant tidal channels that were active during the mid-Holocene, and have since been partially or completely infilled by the deposition of tidal mud and sediments (Woodroffe & Mulrennan 1993). Palaeochannels are associated with sequences of billabongs, freshwater swamps and wetlands, and are therefore particularly vulnerable to saltwater intrusion (Woodroffe et al 1986). As palaeochannels are generally some of the lowest-lying topography within a coastal floodplain, they act as low-land catchments for the development of seepage zones responsible for the initiation of channels (Woodroffe & Mulrennan 1993). Subsequently, palaeochannels across coastal floodplains are preferentially invaded by the expanding network of tidal creeks. Whilst sediment size data have generally been unconvincing in demonstrating this argument, Woodroffe and Mulrennan (1993) suggested that the alluvial deposits of palaeochannels should be more easily eroded than soils that have developed in situ. Given the erodibility of the deposited sediments comprising the palaeochannels, they are generally associated with bordering levee banks of higher relative elevation. Subsequently, palaeochannels, once inundated, tend to confine the pattern of saltwater intrusion.

Woodroffe and Mulrennan (1993) identified the present pattern of saltwater intrusion as a re-invasion of the low-lying coastal floodplains that were once at an elevation above which saltwater could reach. Given that much of the wetland that previously excluded saltwater is now well below the highest spring tide level, then either a relative sea level rise or a lowering of the plains has occurred. Woodroffe et al (1991) note that a net change of sea level over time appears to be negligible and may therefore be disregarded in the subsequent discussion. Suggestions have been made that compaction and consolidation of sediment since their deposition have caused the change (Woodroffe & Mulrennan 1993). Subsidence is evident within deltaic estuaries, although the rate of consolidation and compaction is unknown (Woodroffe & Mulrennan 1993).

As an alternative proposition, Woodroffe et al (1986) suggested that changes in tidal amplitude throughout the rivers of northern Australia may be linked with evidence of recent salt invasion. The elevation of spring high tide water level will increase if a tidal river becomes shorter through meander cutoff, and shallower through shoal formation (Chappell 1988). Research on the South Alligator River by Woodroffe et al (1986) indicated that the river morphology in the lower estuarine reaches has become wider and shallower during its evolution. The present morphology of the South Alligator River is shorter than the former channel due to meander cutoff, and has not experienced meander regrowth (Chappell 1988). Similar changes are likely to have occurred on the East Alligator River over the same period. The geomorphologic changes which have occurred on the South Alligator River are expected to have increased the spring tide by about 0.5 to 1 metre in the upstream reaches of the South Alligator tidal section (Woodroffe et al 1986).

Propositions by Woodroffe et al (1986) and Woodroffe and Mulrennan (1993) relate to long-term changes in floodplain geomorphology, which take place over several thousand years. These provide a context for several higher frequency processes that are likely to contribute to evolution of the floodplain and affect the balance of saline versus freshwater wetlands. The rapidity with which the networks of tidal creeks have expanded and intensified during the past 50 years on the Mary River is indicative of either a trigger mechanism that has moved the floodplain system towards a new morphological state, or short-term fluctuations in atmospheric, fluvial and oceanographic processes.

In the first instance, the direct impact of large numbers of uncontrolled feral buffalo on the erosion of tidal channels has attracted significant attention within the literature. It is a commonly held view that buffalo grazing and trampling along swim-channels have hastened, if not initiated, the extension of tidal influences (Stocker 1970). From an examination of 1950 and 1981 aerial photographs, Fogarty (1982) noted a correlation between the extent of saltwater intrusion and an increase in buffalo on the floodplains. Similar observations have been made on the South Alligator River floodplains (D Lindner pers comm, cited in Finlayson et al 1988). Whilst the buffalo numbers have declined in recent years, due to the an eradication program to prevent the spread of Bovine Tuberculosis (Woodroffe & Mulrennan 1993), an estimated 341 000 animals were present within the lower Mary River plains during 1985 (Bayliss & Yeomans 1989). Furthermore, high production values of buffalo hide in the 1930s to 1940s suggest that buffalo numbers were particularly high around the period when creek networks of both the Mary and South Alligator Rivers began to erode. Since the 1970s, and with the assistance of reclamation work, removal of buffaloes from areas of the South Alligator floodplain has allowed natural regeneration of some of the disturbed areas. Despite these actions, the establishment of dams and levees across tidal channels of the South Alligator and East Alligator Rivers have had varying success in preventing saltwater intrusion (D Lindner pers comm).

In the second instance, the oceanography of van Diemen Gulf warrants closer examination. Basin responses to marked variation in climate between phases of pronounced ENSO activity occur at sub-decadal and longer frequencies. There is evidence of non-stationarity in mean rainfall conditions over the 70 years for which records are available in the Region. Substantial switching, with up to 15% departure each way from the long-term mean, occurs between wetter and drier periods (Carter 1990). These changes are very likely to affect local sea levels and coastal erosion around the shores of the Gulf, precipitation in the stream catchments, river discharge regimes and channel sedimentation. All require further investigation that is beyond the scope of this paper.

1.3 Changes in mangrove distribution

Mangroves are halophytic trees or shrubs that are almost entirely restricted to the upper intertidal zone. They are characterised by adaptations to unconsolidated, periodically inundated, saline and coastal habitats (Woodroffe 1995). Mangrove communities existing within the Alligator Rivers Region form narrow bands along the coast and on tidally influenced creeks and river banks. Given that the young, unconsolidated substrates of mangrove shorelines are continuously exposed to daily tidal oscillations and seasonal flooding, they are naturally unstable or dynamic environments, extending or contracting rapidly in response to relative sea-level changes (Woodroffe 1995). This recognition has led to suggestions that the structure and distribution of mangrove communities may be associated with the tidal creek extension of saltwater influence into freshwater wetlands of the Alligator Rivers Region (Woodroffe et al 1986, Bayliss et al 1997). The proposition is further examined in this paper.

Spatial variations in the distribution of mangroves along the estuarine river systems of the Northern Territory coastline have been investigated relatively extensively within the literature. Broad-scale mapping of much of the coastline has been documented, and relationships between the spatial distributions and environmental factors have been identified (Hegerl et al 1979, Wells 1985, Davie 1985, Finlayson & Woodroffe1996). Past research of mangrove ecosystems and characteristics has documented supportive evidence of a close relationship between mangroves and sea-level fluctuations (Woodroffe 1987, Ellison & Stoddart 1991, Ellison 1993, Semeniuk 1994). It is generally accepted that mangroves are sensitive indicators of changes in relative sea-level and salinity regimes. In light of this, radio-carbon dating of mangrove wood fragments of the South Alligator River has been indicative of sea level changes dating over the past 6000 years (Woodroffe 1987).

In the same context, the spatial extent and patterns of mangrove encroachment along tidal creeks of the Alligator Rivers Region, may be indicative of the processes and extent of saltwater intrusions within the Region. Although detailed recommendations have been outlined, there is no previous record of a long-term monitoring program of mangroves within the Alligator Rivers Region (Bayliss et al 1997). Subsequently, the spatial extent, rates and trends of mangrove growth have not been determined. Given this, the present research determined changes in mangrove distributions along the tidal channels and creeks of the Alligator Rivers Region, as an indicator of the trends of saltwater intrusion.

1.4 Environmental setting

The Alligator Rivers Region is located in the wet-dry tropics of northern Australia, between latitudes 12°S and 14°S. The Region flanks the south-eastern shore of van Diemen Gulf, approximately 120 km east of Darwin. It includes the catchments of four main estuarine river systems; the Wildman, West Alligator, South Alligator and East Alligator Rivers. Much of the region is incorporated in Kakadu National Park, which is an area of international significance for both cultural and heritage values.

1.5 Climate

The climate of the northern coast of Australia is monsoonal, with a highly seasonal rainfall regime that defines two distinct seasons (Woodroffe et al 1986). The pronounced seasonality of the climate may be a significant factor in affecting regional vulnerability to saltwater intrusion, as the prolonged Dry season is conducive to saltwater ingress (Woodroffe & Mulrennan 1993). The Wet season is characterised by heavy periodic rains, is generally hot and humid and occurs during the period November to March each year (McQuade et al 1996). Monsoonal troughs and tropical cyclones directly related to monsoon activity are the dominant rain producing systems. The result is a hot and rainy Wet season that lasts for three to four months, although both the onset and duration may fluctuate from year to year (Lee & Neal 1984). In contrast to this, very little rain falls during the Dry season months, from May to September.

The average annual rainfall of the region between Darwin and the Alligator Rivers is between 1300 and 1600 mm (Whitehead et al 1990). The monsoonal climate is characterised by warm to hot temperatures throughout the year, accompanied by high relative humidities of about 80% (Lee & Neal 1984). Mean daily minimum and maximum temperatures for the Alligator Rivers Region are 19°C and 30°C in July (the Dry season), and 25°C and 33°C in November at the onset of the wet (McAlpine 1976).

2 Aim

The aim of the research reported here was to determine the spatial extent and rate of saltwater intrusion in the Alligator Rivers Region, in the eastern half of van Diemen Gulf. This required compilation of information relating to the growth rate and distribution patterns of tidal creek extension and mangrove encroachment, as an indicator of the extent of saline influence. Hence, the broader aim of this research will be achieved through following more specific objectives to:

- map the tidal channels of the Alligator Rivers Region for each set of available aerial photography (table 1: 1950, 1975, 1984 and 1991) in a manner consistent with that used by Knighton et al (1992) for the adjoining area of the Mary River floodplains;

- determine the rate and spatial extent of tidal creek expansion and mangrove encroachment within the Alligator Rivers Region;
- where appropriate, compare changes in the Alligator Rivers Region with those that have occurred around the southern shores of van Diemen Gulf over the same time period.

3 Methods

This research involved interpretation of aerial photographs and topographical maps to reconstruct the general pattern of tidal creek and mangrove expansion in the Alligator Rivers Region. Detailed maps of the changes in the pattern of tidal creeks and the distribution of mangroves were constructed from the aerial surveys. Qualitative analysis techniques were utilised to determine the rates and topological properties of the changes observed.

3.1 Changes to the distribution of tidal creeks and mangroves

Tidal creek expansion and mangrove encroachment of the Wildman, West Alligator, South Alligator and East Alligator Rivers, were reconstructed from aerial photographs for the years 1950, 1975, 1984 and 1991. The aerial photographs were flown during the Dry season of each year. This aided determination of the tidal reach of the creeks, as tidal flows dominate over fresh floodwaters at this time. Although the photographs were seasonally consistent, they varied in scale and quality (table 1). To overcome the inconsistencies between photographs, mapping of tidal creeks was standardised using the method described in Knighton et al (1992).

Maps of the tidal creeks and mangroves were drawn at a working scale of 1:100 000 so that overlays could be prepared to aid comparison on the presence or absence of streams. Overlays also enabled comparison of topologic properties of the tidal creeks, and the spatial distribution pattern of mangroves.

3.2 Network properties

Geometric and topologic properties of the Wildman, West Alligator, South Alligator and East Alligator River networks were determined as measures of the rate and modes of tidal creek and mangrove growth over the years 1950 to 1991. Network magnitude is a topologic variable corresponding to the number of exterior links of first order channels (Shreve 1967), and was used as a measure of network size. Mangrove area was calculated from the maps constructed for each year, 1950, 1975, 1984 and 1991, by measuring the paper weight of the respective areas cut from enlarged maps, and determining the ratio of g/km^2. Mangrove area was used as a measure of the rate of mangrove encroachment. The trends of network growth and mangrove expansion are depicted in graphical format for each river system and related to the spatial distribution patterns.

4 Results

4.1 Gross distribution of tidal creeks and mangroves between 1950 and 1991

Since the late 1940s – early 1950s, the estuarine rivers of the Alligator Rivers Region have expanded their tidal influence along extending creek lines and the resultant changes in the saltwater reaches have been coupled with extensive mangrove encroachment. The trends of change are separately described for each of the river systems.

4.2 South Alligator River

From 1950 to 1991, existing tidal creeks of the South Alligator River developed though a combination of headward extension and tributary growth. In 1950, tributary development was relatively limited in the sinuous, cuspate and upstream segments of the river (as described by Chappell 1988), whilst the most extensive network of tributaries was within and extending from a large palaeochannel on the eastern flank of the estuarine funnel.

By 1975, the creeks, which appeared relatively inactive in 1950, had extended in the middle and upper reaches of the South Alligator River. A number of creeks had successfully invaded the series of palaeochannels flanking the sinuous and meander segments of the river. From 1975 to 1991, tributary growth remained active within the confines of the palaeochannel boundaries along the meanders of the South Alligator River, whilst they remained limited elsewhere. The importance of small topographical development is evident from this trend of growth.

Expansion of the tidal influence along extending creek lines of the South Alligator River is reflected by spatial changes in the shoreline distribution of mangroves. Since 1950, mangroves extended along the main tributaries of the South Alligator River as they became increasingly active. In 1950, mangroves had extensively colonised the shoreline and main channels of the estuarine funnel, whilst they encroached the sinuous and cuspate segments of the river only in patches. Few mangroves colonised the upstream segment of the river. By 1991, mangroves had extended approximately 15 km upstream, invading tributaries dominated by fresh floodwaters. Mangroves had also encroached the higher order channels from the sinuous and cuspate meanders and along the lower creek lines within the palaeochannels.

4.3 East Alligator River

The mouth of the East Alligator River lies approximately 25 km north-east of the South Alligator River within the Kakadu National Park boundary. From 1950 to 1991, the branching tributaries from the East Alligator River extended in a similar trend to that described for the South Alligator River, through a combination of headward extension of the main channels and the growth of tributaries (Cobb 1997).

In 1950, two main creeks dominated the sinuous and cuspate segments of the East Alligator River. The creek extending from the sinuous segment had not extended further than two kilometres south of the river channel, with few headwater tributaries. Similarly, the main tributary of the cuspate segment, the Magela Creek, had not extended south further than five kilometres. Small creeks branched from each river segment, although significant tributary development was limited on the East Alligator River at this time.

By 1975, both of the main channels in the meander river segment had bifurcated into more distinctly defined tributary networks. The tidal creeks in the upstream segment of the East Alligator River extended predominantly within the confines of the palaeochannels, mainly through headward growth with few branching tributaries. Whilst the most active creeks were those invading the lower topography of the palaeochannels, the single creeks of the estuarine funnel had also extended since 1950.

Tributary growth continued in the upstream segment within the palaeomeanders from 1975 to 1991. Some of the small tributaries flanking the estuarine funnel extended south as far as two and a half kilometres. Little further extension occurred in either of the two main tidal creeks of the meander segment of the river.

Since 1950, mangroves accompanied the expansion of creek lines on the East Alligator River as they became more tidally active. In 1950, mangroves flanked the shoreline boundary of the estuary mouth, and sparsely colonised shoals and point bars of the cuspate meanders. At this stage mangroves were generally limited to the main river channel in the meander and upstream segments of the river, although they had begun to encroach the Magela Creek.

By 1984, mangroves had rapidly encroached the main tidal channel on the southern flank of the sinuous segment of the river, which had not been encroached in 1975. The period of mangrove encroachment of the tidal channel corresponds to a lapse in the rate of tidal creek extension.

By 1991, the spatial distribution of mangroves on the East Alligator River was no longer confined to the main river channel. Mangroves had colonised the shoreline of the funnel more densely, and had encroached some of the channels which extended from the river mouth since 1975. The tidal channel and branching first order creeks of the sinuous river segment were densely colonised by 1991. The point bars and shoal forms of both the sinuous and cuspate meanders were flanked with mangroves, and mangroves encroached the palaeomeander cutoff where the Magela Creek joins the East Alligator River.

4.4 Wildman and West Alligator River

The Wildman and West Alligator Rivers are the nearest western neighbours to the South Alligator River, and lie within the western flank of Kakadu National Park. Since 1950, tidal creeks of both the West Alligator and the Wildman Rivers have developed, although not at the rate or to the extent as that observed on both the South and East Alligator Rivers. Both rivers exhibited marked changes in the shoreline distribution of mangroves, suggesting expansion of the tidal reach such as that observed coupling the dramatic creek extension on the South Alligator and East Alligator Rivers (Cobb 1997).

The trends of mangrove colonisation on the Wildman and West Alligator Rivers since 1950 are similar to those observed for the South Alligator and East Alligator Rivers. Mangrove encroachment has occurred along the main tributaries of both the West Alligator and Wildman Rivers, and along smaller creek lines as they became increasingly active. Mangroves densely flank the shoreline of both river systems, with colonisation becoming more sparse in the upper reaches of the rivers. The fluvial segments of both rivers have a limited distribution of mangroves, although from 1950 to 1991 mangroves had extended approximately four kilometres upstream on the West Alligator River.

5 Analysis

5.1 Tidal creek extension

Using network magnitude as a measure of network size, the South Alligator River has experienced an exponential rate of growth, with a significant increase in growth rate post 1975. Similarly, the Wildman River experienced an exponential rate of growth, with an increase in growth rate post 1984, although data for 1974 was not available. In contrast to this, the growth rates of the East Alligator and West Alligator Rivers show linear trends, with rates of growth remaining relatively consistent from 1950 to 1991 (Cobb 1997).

The rates of tributary growth from 1950 to 1991 varied between the Wildman and the South Alligator River, although the trends of growth were both exponential. There were insufficient data points of network magnitude over time to establish an accurate exponential regression line for the South Alligator and Wildman River growth trends. However, it is evident the rates of growth changed over time. From 1984 to 1991, the South Alligator River expanded more rapidly than the Wildman over the same time period, with an increasing network magnitude of 20 as opposed to 10. The South Alligator River also attained a significantly higher magnitude (233) as opposed to the Wildman (75), although this may be attributed to the size difference between the river systems and main tributaries.

Although both rivers experienced a linear growth rate, the rates of growth between 1950 and 1991 varied greatly between the East Alligator River and the West Alligator River. From 1950 to 1991 the network magnitude of the East Alligator River increased by 132 whilst over the same period the West Alligator River increased by 41.

Despite an overall exponential rate of tidal creek growth on the South Alligator River, the characteristics of network growth varied with the morphological changes in the river channel, defined by Chappell (1988). Little growth had occurred in the estuarine funnel and sinuous segments of the river until 1975, after which tidal creeks began extending in a linear or arrested pattern, with a slow rate of change. In the upstream reaches of the river, including the cuspate meanders and fluvial segment respectively, network growth occurred in a linear and weakly exponential trend.

In contrast to the trends observed for the South Alligator River, linear growth was observed for both the funnel and fluvial segments of the East Alligator River, whilst arrested development occurred within the meanders.

5.2 Spread in the distribution of mangroves

The Wildman, West Alligator, South Alligator and East Alligator Rivers each experienced an exponential rate of mangrove growth from 1950 to 1991, although the rates of change between the rivers were varied. Mangrove expansion had occurred most rapidly on the West Alligator and South Alligator Rivers, with the most significant growth rates occurring post 1975. From 1984 to 1991, total mangrove area on the South Alligator and West Alligator Rivers increased by 13 and 9 km^2 respectively. Over the same period, mangrove growth on the Wildman and East Alligator Rivers increased by 3 and 4 km^2 respectively.

Despite an overall exponential rate of mangrove growth on the South Alligator River, the trends of mangrove growth varied with the morphological changes in the river channel. Mangrove growth occurred in a weakly exponential trend in the upper reaches of the river, and in the estuarine funnel. Little growth occurred from the meanders of the South Alligator until 1984, after which time both the sinuous and cuspate segments experienced a period of rapid mangrove encroachment.

On the East Alligator River, the trends of mangrove growth from 1950 to 1991 were similar to that observed in the South Alligator River. However, unlike the weakly exponential trend observed for the South Alligator River, mangrove growth occurred in an arrested trend in the upper fluvial segment of the East Alligator River.

6 Discussion

Changes in the spatial characteristics and distribution of tidal creeks and mangroves in the Alligator Rivers Region have been reconstructed from aerial photography to document change over the past 50 years. Analysis and interpretation of changes in network magnitude of tidal creeks have determined the rate and trends of tidal creek extension on the different river systems in the Alligator Rivers Region. Similarly, the rate and spatial patterns of mangrove colonisation in the Alligator Rivers Region were described for each river system, and paralleled with the rate and growth trends of the tidal creeks.

The changes indicate that between 1950 and 1991 the saltwater reach has expanded along extending creek lines. A similar trend of saltwater intrusion has been observed and mapped on the Mary River plains, west of the Alligator Rivers Region. Knighton et al (1992) noted that the two main creeks, Sampan and Tommycut Creeks, have experienced rapid tidal creek extension since the late 1930s – early 1940s. Using network magnitude as a measure of the network size, both creeks experienced an exponential rate of growth. Unlike the growth trends which have occurred on the Mary River plain over the same time period, the East Alligator and West Alligator Rivers have developed in a linear trend. Similarly, tidal creek development on the South Alligator River and the Wildman River has been only weakly exponential. The exponential growth rate experienced by Sampan and Tommycut Creeks befits a growth trend that conforms with trends observed in experimental networks (Knighton et al 1992). Unlike the Mary River catchment, which is drained by a number of dendritic tidal creeks that bifurcate from the sea, the Alligator Rivers Region is drained by a series of well developed estuarine channels. Along each of the main river channels, tidal creek growth has occurred in localised areas of extension and tributary growth. The predominantly linear trend of network growth determined for the main rivers of the Alligator Rivers Region may reflect the absence of large expanding dendritic creek networks, such as that formed on the Mary River plains.

Despite variation in network expansion between the tidal rivers of the Alligator Rivers Region and their western neighbour, the Mary River floodplains, both floodplains have exhibited similar trends of growth. Knighton et al (1992) noted that the pre-existence of channel lines provided the principle routes for main channel extension on the Mary River.

Similar trends of tidal creek expansion were observed for the South Alligator and East Alligator Rivers. The most vigorous rates of tidal creek extension, dominantly through headward extension, were concentrated within low-lying palaeochannel swamps of the South and East Alligator Rivers, and tributary growth was confined within the palaeochannel boundaries. This trend of growth is indicative of the significance of slight topographical variations on tidal creeks development.

Knighton et al (1992) drew further attention to the impact of buffalo swim channels on the trends of saltwater intrusion on the Mary River plains. The distribution of buffalo swim channels in the Alligator Rivers Region have not been indicated on the map compilations of recent changes. Given the relationship observed between main swim channels and tidal creek extension on the Mary River plains, areas of rapid growth in the Alligator Rivers Region may be partly attributed to buffalo activity. However, this proposition needs closer examination.

7 Conclusions

Saltwater intrusion though tidal-creek extension has been identified as a major coastal problem in the Alligator Rivers Region (Bayliss et al 1997). Whilst the trends of saltwater intrusion have been well documented in the literature for the Mary River plains and observed elsewhere in the Alligator Rivers Region, the geographic extent of the problem, and the spatial variations in the rates of change had not been determined in detail.

The aim of this paper was to determine the spatial extent and rate of saltwater intrusion in the Alligator Rivers Region. Documentation of the recent tidal creek and mangrove changes in the Alligator Rivers Region will enable direct comparison of the spatial extent of the estuarine channels in the region with adjacent areas along the southern shoreline of van Diemen Gulf.

Prior to this research, comparison between different regions was difficult due to variations in both scale and format. Maps of recent tidal creek extension and mangrove encroachment of the Wildman, West Alligator, South Alligator and East Alligator Rivers extend our knowledge of the geographic extent of saltwater intrusion, spatial variation in the rates of change, and the area of wetlands affected by saltwater intrusion.

First, the rapid rates of tidal-creek extension reported from the vicinity of the Mary River are now understood to apply to the wetlands of the Alligator Rivers Region. Saltwater intrusion of freshwater wetlands has occurred up to 18 km in the Wildman River, 44 km in the West Alligator River, 105 km in the South Alligator River and 76 km in the East Alligator. The total area of wetland affected by saltwater intrusion is substantial and is currently being established by a Geographic Information System interpretation of the available information.

The research described herein contributes to documentation of the trends and extent of saltwater intrusion of the floodplains of the van Diemen Gulf. Future research should incorporate continued monitoring of changes, processes and rates of saltwater intrusion across the southern shores of van Diemen Gulf. In addition to mapping the progress of tidal creeks and mangroves, monitoring should also aim to include documenting the extent of salt flats. Whilst the extent of the problem has been well defined in the literature, and the trends of saltwater intrusion are generally well-understood, little research has addressed the mechanics or processes of saltwater intrusion. There is also a need to determine whether the rate at which tidal creeks are extending varies for river reaches with markedly disparate tide versus flood discharge relationships. Given the threat saltwater intrusion poses on the freshwater wetlands within the Alligator Rivers Region, establishment of a monitoring program is an essential task for management. However, a full appreciation of the different processes contributing to saltwater intrusion is fundamental to planning of a monitoring program.

8 Acknowledgments

Support for the project was provided by the Department of Geography at the University of Western Australia (UWA) and the Environmental Research Institute of the Supervising Scientist at Jabiru. Parks Australia North provided access to several sets of aerial photography. Whilst all comments made in the paper necessarily reflect our opinions and not those of the institutions for whom we work, we are particularly grateful to Arthur Johnston and Max Finlayson (***eriss***) and John Dodson (UWA), as well as to personnel from both institutions for their continued encouragement and support.

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Paper 9 Changes in mangrove distribution

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Abstract

Mangroves occur within the transition zone between sea and land providing coastal stability. They are an important element in consideration of the possible impacts of climatic change and sea-level rise. Therefore, an understanding of the mangrove communities and their environment is a necessary component of any assessment of coastal change in the Alligator Rivers Region. This paper identifies previous efforts to study mangroves in the region and attempts to highlight priorities for, as well as develop a baseline from which future study may proceed.

This study is a sub-component of the program for assessment and monitoring of coastal change in the Alligator Rivers Region, initiated by the Environmental Research Institute of the Supervising Scientist at Jabiru, in the Northern Territory of Australia.

Key words: mangrove research, Alligator Rivers Region, Kakadu National Park, coastal change

1 Introduction

Mangroves are halophytic trees or shrubs which dominate sheltered, muddy, intertidal environments (between mean and high tide levels) along tropical and subtropical shorelines (Woodroffe 1995, Messel et al 1979). Australia has significant mangrove resources, covering an area of 11 500 km^2, of which 40% occurs in Queensland, 36% in the Northern Territory, and 22% in Western Australia (Galloway 1982). Australia has the third largest mangrove area in the world, after Indonesia and Brazil.

The Alligator Rivers Region (fig 1) was one of eight regions assessed by the Department of Environment, Sport and Territories (DEST) program 'Vulnerability to Climate Change' in 1995. A mangrove monitoring program in conjunction with the existing freshwater monitoring program at the Environmental Research Institute of the Supervising Scientist was identified as a necessary management requirement. The rationale underlying the recommendation was that the structure and distribution of mangrove communities may be linked with coastal stability as well as encroachment of tidal streams into freshwater wetlands.

Various components of climate change and how they are expected to influence mangrove communities globally have been dealt with extensively (Pernetta 1993, UNEP 1994, Ellison 1994). With these references, mangrove communities of this region will be studied, to develop an understanding of the processes acting upon them, as well as their role as potential sensitive indicators of environmental change.

Alligator Rivers Region

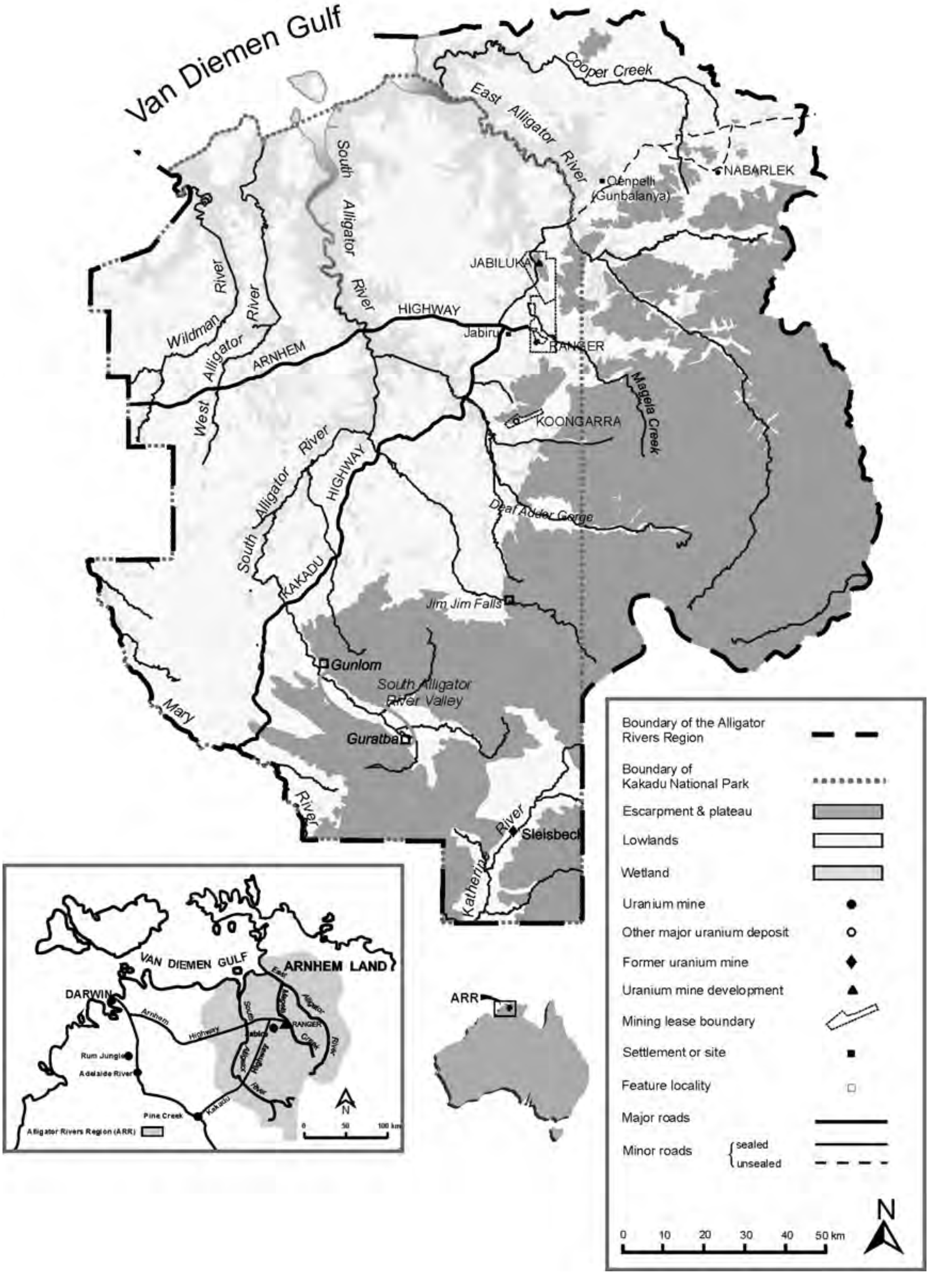

Figure1 Location diagram for the Alligator Rivers Region

2 Aims

This study aims to define the existing baseline level of information regarding mangrove distributions available for the Alligator Rivers Region. It is a sub-component of the coastal assessment and monitoring program for the Alligator Rivers Region, initiated by the Environmental Research Institute of the Supervising Scientist, which covers a range of biophysical processes, including shoreline movement change and oceanographic variability.

Review of this information shall define future data collection and analysis programs to identify changes in mangrove distribution within the Alligator Rivers Region. It is the intention of the program to develop the capacity 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, as well as the wider Alligator Rivers Region.

Optimally, it is intended that the program shall be developed such that the following stages may be reached:

- definition of the present extent of mangroves in the Alligator Rivers Region, providing a baseline with which to compare future monitoring; and
- determination of changes occurring within recent history, to derive correlations with known changes to the biophysical environment, and assist with predictions of anticipated development.

Estimation of prehistoric changes shall be included within geormorphological studies of the Alligator Rivers Region by the Environmental Research Institute of the Supervising Scientist. Information from the studies will be of relevance to the coastal assessment and monitoring program, as stratigraphic methods may provide a record of climatic extremes and corresponding response of mangrove distributions.

3 Objectives

Objectives of this study are:

- conduct a literature search to determine the extent of previous investigations regarding mangrove distributions within the Alligator Rivers Region;
- determine available methodologies and current best practices for monitoring of mangrove distributions;
- assess the information available to describe mangrove distributions, existing and historical;
- define projects to enable the existing and historical mangrove distributions to be assessed;
- identify means for monitoring future changes to mangrove distributions.

4 Background

Mangroves occur between mean and high tide elevation on low energy, sedimentary shorelines of the tropics and sub-tropics. Woodroffe (1995) suggests that mangrove shorelines are naturally dynamic with some places eroding and others accreting, but that their response to relative sea level change will reflect the natural change of the system. It is indicated from past analogues that the close relationship with sea-level position of mangroves renders them particularly vulnerable to disruption by future sea-level rise (Woodroffe et al 1988, Woodroffe 1995, Ellison & Stoddart 1991).

4.1 Mangrove studies in northern Australia

Woodroffe (1995) states that within the Top End of Australia the most extensive Holocene coastal and estuarine plains occur along the southern shore of van Diemen Gulf which includes the Alligator Rivers Region, and the adjacent Mary and Adelaide River catchments. These plains contain some of the largest remaining areas of freshwater wetlands in Australia. However, stratigraphic studies indicate that this was not always the case, with the current freshwater wetlands developing only during the last few thousand years, replacing extensive mangrove forests (Woodroffe et al 1989). The stratigraphic evidence on the coastal plains of the South Alligator River, the Adelaide and the Mary Rivers suggests a domination of coastal progradation (including episodic chenier formation) with the most rapid deposition occurring from 5000 years to 3000 years BP, with little activity since then (Woodroffe et al 1989, Woodroffe & Mulrennan 1993). The existence of mangroves within the stratigraphic record is a key to past shorelines and sea-levels indicating the possible scope of changes in and around the region.

Woodroffe and Mulrennan (1993) and Knighton et al (1992) have documented dramatic recent changes to the Lower Mary River floodplain, associated with salt water intrusion and upstream expansion of the tidal creek network (fig 2). These dramatic changes have been associated with the death of freshwater wetland communities involving the loss of 60 km^2 of *Melaleuca* forest, and upstream invasion of mangroves. There are a number of possible reasons for these events, including relative sea-level rise (Woodroffe 1990). Extension of tidal creeks and consequential mangrove development has occurred on at least two river systems within Kakadu National Park (Finlayson & Woodroffe 1996, Cobb 1997). Clark and Guppy (1988) claim that a sea-level rise of 0.5 to 1.0 m would transform the Alligator Rivers freshwater wetlands into a large mangrove swamp similar to that existing during the mid Holocene.

Distribution of mangroves along the northern Australian coastline has been reasonably well investigated with broadscale mapping for much of the coastline and identification of relationships with environmental factors (Hegerl et al 1979a,b, Dames & Moore 1984, Semeniuk 1993, Blackman et al 1993). In the Northern Territory the Alligator Rivers Region and Darwin Harbour have received particular attention (Hegerl et al 1979a,b, Wells 1985, Dames & Moore 1984, Davie 1985, Finlayson & Woodroffe 1996).

4.2 Mangrove studies in the Alligator Rivers Region

The sub-coastal floodplain and intertidal wetlands of Kakadu National Park occupy almost 2200 km^2 of which approximately 3% (72 km^2) represents mangrove communities (Bayliss et al 1997). These mangrove communities form narrow bands along the coast and on tidally influenced creek and river banks. Thirty eight species of mangrove have been identified and recorded within the region (Wightman 1989).

Mangrove plant communities along the coast in the Alligator Rivers Region may be strongly zoned along the intertidal topographic gradient (Specht 1958a,b, Hegerl et al 1979a,b). Zonation suggests that the conditions for propagule recruitment or the competitive abilities of different species are highly sensitive to relatively small changes in the tidal flooding regime. Freshwater flow, soil type, coastal setting, climate and drainage are also important controlling factors (Chapman 1977, Bunt et al 1982, Semeniuk 1993). The most common species is *Avicennia marina* which can tolerate a wide salinity range (Macnae 1966). *Rhizophora stylosa* is found in highly saline areas inundated regularly by tides and occurs either as a pioneer species or in monospecific stands behind other pioneering species. *Ceriops tagal* is also a common species and, although intolerant of freshwater, can colonise the landward, unconsolidated clay edge of the mangal.

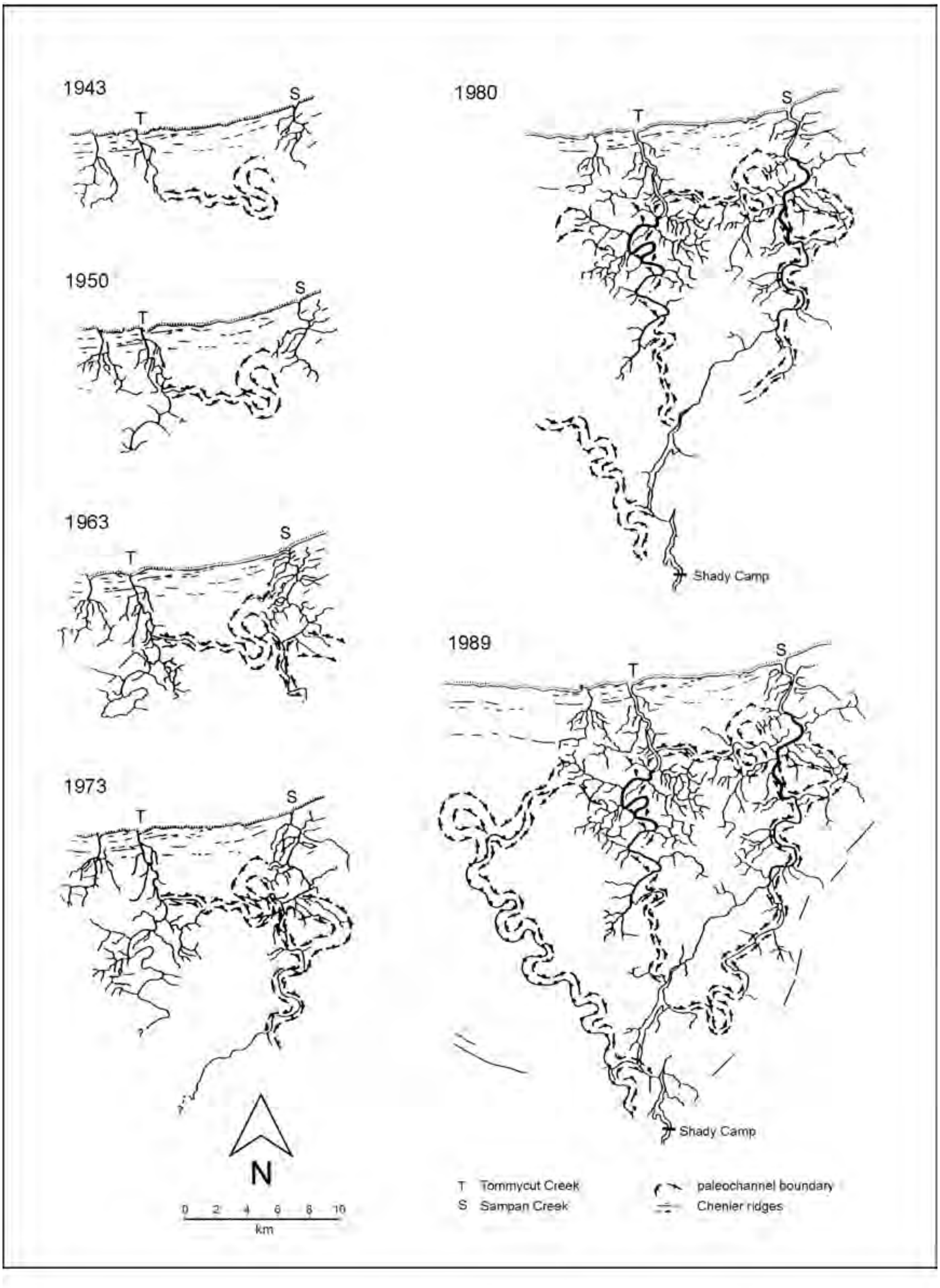

Figure 2 Expansion of Sampan and Tommycut Creeks, 1943–1989 (from Knighton et al 1992)

Hegerl et al (1979a,b) give a common pattern of mangrove zonation along the coast of the Alligator Rivers Region:

Sonneratia alba → *Rhizophora stylosa* → *Ceriops tagal* → *Avicennia marina*

(at the seaward edge) (at the landward margin)

In the event of a rise in relative sea level of less than 50 cm in the Alligator Rivers Region, the coastal mangrove communities may enter a period of continuous self-adjustment to the receding shoreline (Bayliss et al 1997). Successive generations of mangroves will, relative to their parent populations, be recruited at more landward positions. Parental mangrove populations will be eliminated at the seaward edge of their zone of tolerance. Overall plant stature may be inversely related to the rate of relative sea level rise as plants may not be able to attain their full potential height before changes to the tidal flooding regime cause their demise. Coastal mangrove trees subject to rising relative sea levels may therefore not achieve the heights of those present today.

Davie (1985) highlights the instability of the estuarine environment and shows that mangrove communities along the South Alligator River exist in a variety of stages of colonisation and degradation reflecting a history of responses to ever changing stream channel dynamics. His conclusion is highly relevant:

> The vegetation patterns described … illustrate an environment dominated by physical change driven by powerful physical and climatic forces which characterise the macrotidal monsoonal environment. Vegetation change is taking place over several scales in time and space.

Mangrove settings include some of the most spatially and temporally unstable environments in the Alligator Rivers Region; a consequence of having young, unconsolidated substrates continuously exposed to the cut and thrust of daily macro-tidal oscillation and annual floods. Mangrove communities are thus an expression of success in a contemporary environment dominated by change. However, from an historical perspective, their survival to the present is also an expression of their resilience to the various sea-level fluctuations that have occurred throughout recent geological time.

Rising relative sea-level will cause sub-coastal flats to be flooded more extensively by tides possibly resulting in rapid inland development of tidal channel networks (Knighton et al 1991). Because of the low gradient of the coastal plains, particularly in the Alligator Rivers Region, small rises in relative sea-level may result in relatively large areas becoming affected by salt water intrusion.

Although no studies have been conducted in the Alligator Rivers Region, information concerning the effects of storm damage to coastal mangrove stands have been conducted elsewhere in the Northern Territory. Bardsley (1985) showed that many mangrove species resprouted vigorously following cyclone impact, despite sustaining extensive damage. However, species in the family Rhizophoraceae were a notable exception; if the small branches were stripped they did not regenerate.

No mangrove productivity studies have been conducted in the Alligator Rivers Region. Woodroffe et al (1988) determined the production rates of litter from an estuarine mangrove stand in Darwin. They demonstrated a Wet season peak in litter production and that different mangrove zones had very different litter production rates. In the second year of the two year study, litter production was consistently lower than the first, although the percentage reduction was not consistent across all sites.

The majority of mangrove work completed in Kakadu can be found in the following:

- Cobb SM (1997) Channel extension and the geomorphology of tidal creeks in Kakadu National Park, Northern Territory. Honours thesis, Department of Geography, University of Western Australia, Perth.
- Hegerl EJ et al (1979–1982) The Kakadu National Park mangrove forests and tidal marshes., Volumes 1, 2, 3 & 4, Australian Littoral Society, Unpublished report to

ANPWS, Canberra. (These volumes are comprised of a literature review, a feasibility study, the research program and the preliminary results.)

- Good NM (1994) Factors influencing leaf litter processing in subtropical and tropical Australia. Honours Thesis, Griffith University, Brisbane. (Honours thesis that resurveyed transects previously surveyed by Hegerl et al 1981)

Several unsuccessful attempts have been made to obtain the final report from, and the grid references for, the transects surveyed in the above mentioned Hegerl et al (1981) paper. Attempts continue. Some photographs have kindly been supplied by one of the authors.

There are also several descriptive overviews of the mangrove environments, such as Finlayson and Woodroffe (1996) and Woodroffe (1988, 1990 & 1995).

5 Available methods

Woodroffe et al (1991) reconstructed network expansions of the Mary River using detailed maps drawn from aerial photographs under 8x magnification. They stated that because the photographs varied in scale and quality there was a problem ensuring compatibility between dates. This type of mapping produces good results if the data sets are correct and compatible. Further exploration into this method should take place including using computer software packages that allow aerial photographs to be scanned and then compared.

Cobb (1997) mapped channel expansions and mangrove extensions of sites on the South and East Alligator Rivers using aerial photographs and topographic maps. Position fixing and photogrammetric correction was enabled by using a differential GPS to map the same sites. The combination of aerial photography with dGPS position fixing enables high spatial veracity, with coverage over large distances, for terrain that is inhospitable to standard cadastral surveying techniques.

Suitable techniques for ecological monitoring of mangroves are rare but do exist. Expertise from the Australian Institute of Marine Science is available to assist in determining appropriate methods (Ellison, pers comm 1998).

6 Proposed studies and tasks

At a steering committee meeting for the coastal assessment and monitoring program, various important tasks were identified. These are listed below (not in order of priority).

- Map extent of mangroves along the coastline and river systems of the Alligator Rivers Region, using aerial photography. The most recent aerial photography of the Alligator Rivers Region was flown for ANCA (now Parks Australia) in 1991 (Scale – 1:25 000) and this may be used to establish the mangrove monitoring program baseline. Cobb (1997) has mapped various reaches of the South Alligator River using aerial photography.
- Determine changes in mangroves from historical records such as aerial photographs and old topographic maps. The earliest known aerial photography for the Alligator Rivers Region was in 1943 (scale 1:30 000) and includes only the coastal zone. A more comprehensive aerial photography coverage was flown in 1950 at a scale off 1:50 000. Further aerial photograph runs for the Alligator Rivers Region are available from 1975, 1984 and 1991.
- Comparison of the distributions of mangroves from early and recent photographs could enable the determination of change over approximately 50 years. Cobb (1997) has shown

that mangrove extension was very evident between the years 1950 and 1991 on several creeks along the South Alligator River. This mapping was done at a scale of 1:100 000.

- Place the interpretation of future change in context through the evaluation of past longevity and maintenance of mangrove vegetated habitats by examination of stratigraphy and palaeoecology.
- Survey existing distribution of mangrove communities by airborne (helicopter) video photography and GPS survey.
- Assess the usefulness of Spatial Information Technology in mapping mangrove areas. It is not known how useful satellite imagery will be with regard to species mapping due to the ground resolution or pixel size and the fringing nature of the mangroves.
- Initiate surveys of mangrove species distribution and community structure. Utilise effective standard mangrove survey techniques as suggested by Ellison (1996 pers comm).
- Liaise with other people, particularly in the NT who are working with mangroves.
- Undertake productivity studies of existing mangrove habitat. This can hopefully be an indicator of ecosystem health. No mangrove productivity studies have been done in the Alligator Rivers Region. Appropriate techniques and relevant comparisons exist as Woodroffe et al (1988) determined the production rates of litter from an estuarine mangrove stand in Darwin.

7 Comments

There is considerable overlap between several of the proposed projects within the coastal assessment and monitoring program. Although these have been identified as individual projects, certain components should be undertaken at the same time to reduce costs and staff time. In particular, it should be feasible to combine fieldwork for establishment of the survey framework and ground truthing of the available benchmarks, with the mangrove surveys, determination of existing shoreline condition, and field examination of the salt flats.

8 Conclusions

This study has identified studies of mangrove distributions in the Alligator Rivers Region and the broader northern Australia. Studies in the Alligator Rivers Region have typically examined relatively small sections of coastline, rather than evaluating the mangrove distribution as a whole.

Methods for the assessment and monitoring of mangrove distributions have been examined:

- Photogrammetry has been recognised as the most readily available technique for the analysis of mangrove distributions and comparison with historic distributions. Possible advances through the use of digital technology and manipulation using a spatial information system require further investigation.
- Monitoring techniques for mangrove systems are available. It is recommended that further discussion with AIMS be undertaken to more clearly define program needs and practices.

Recommendations for further progress include:

1. Undertake photogrammetric mapping of mangrove distributions using the most recently collected photography for the Alligator Rivers Region;

2. Undertake comparative photogrammetric mapping of mangrove distributions within the historic time frame for the Alligator Rivers Region. As a minimum, the 1950 photography run should be studied. However, preferably, 1975 and 1984 mangrove distributions should also be examined.
3. Further evaluate possible monitoring techniques, including aerial video, and remote sensing methods; and
4. Undertake surveys of mangrove species distribution, community structure and productivity. Establishment of the sampling areas and frequency should be undertaken in consultation with the Australian Institute of Marine Science.

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Chapter 5 Application and accountability

5.1 Formal provisions for research in Kakadu National Park

Research carried out in Kakadu is done under the auspices of either the Kakadu Board of Management and Parks Australia or the Environmental Research Institute of the Supervising Scientist. Formal provisions for this are made in the *Kakadu National Park Plan of Management 1998–2003* (Kakadu Board of Management and Parks Australia 1998). The Environmental Research Institute of the Supervising Scientist also operates in its own right under the provisions of the *Environment Protection (Alligator Rivers Region) Act 1978*.

Potential applications of the coastal monitoring program are indicated in the *Kakadu National Park Plan of Management*:

> Research and surveys carried out in Kakadu provide baseline information about natural and cultural resources and visitor use of the Park. Monitoring measures whether the park's natural and cultural resources have changed and how they have changed; how people using the Park affect the Park; helps to assess how effective Park management programs are. Research, surveys and monitoring give Parks Australia and the Board information that can help them to decide how to manage the Park as well as possible.
>
> Research, surveys and monitoring in Kakadu also benefit the wider community. For example, wildlife monitoring and visitor surveys in Kakadu give useful information for regional conservation programs, local Aboriginal enterprises and the tourist industry. (Kakadu Board of Management and Parks Australia 1998, 179).

More specific applications should be identified for each component of the monitoring program as it evolves. For example, identification of large-scale oceanographic processes in van Diemen Gulf have ramifications for potential solution of problems associated with salinisation of coastal wetlands in the Mary River region as well as for development of coastal floodplains in Kakadu. Responsibility for translating information that is gathered in the coastal monitoring program to recommendations for implementation by government and community management agencies rests with agencies contributing to specific projects.

5.2 Project administration

The coastal monitoring program is administered by the Environmental Research Institute of the Supervising Scientist during 1996 to 1998 and advised by a Steering Committee convened for the purpose.

5.2.1 Roles of the Environmental Research Institute of the Supervising Scientist

The Environmental Research Institute of the Supervising Scientist is established under the *Environmental Protection (Alligator Rivers Region) Act 1978* Part 4 as the Alligator Rivers Region Research Institute. It exists primarily to undertake independent research, on behalf of the Australian community, to establish the best methods available for the protection of people and ecosystems in the Alligator Rivers Region of Australia's Northern Territory both during and following mining in the region. Its core activities focus on:

1. The effects of mining, particularly uranium mining, in the Alligator Rivers Region, which contains Kakadu National Park.

2. The protection and management of the wetlands of northern Australia.
3. Other specific environmental issues on behalf of the Australian Government.

The purpose of the coastal monitoring program was two-fold. First, the monitoring program was intended to identify environmental changes in the Alligator Rivers Region of the Northern Territory that are likely to affect management of the Kakadu National Park and its surrounds. This includes on-going assessment of potential environmental changes likely to result from uranium mining activities at Ranger and Jabiluka. Second, it provided a mechanism to coordinate and evaluate ongoing environmental monitoring and research programs being conducted by the Environmental Research Institute of the Supervising Scientist and other agencies.

The coastal monitoring program established work undertaken by the Environmental Research Institute of the Supervising Scientist in a broader community context. Its mission was to develop a regional capacity to measure and assess variation in biophysical processes on the floodplains and coast of the wet-dry tropics of northern Australia. In doing this it provided an information system detailing environmental variability for use by all people with interests in management of the coastal zone of the wet-dry tropics. Specific investigations have been commenced in Kakadu National Park and the wider Alligator Rivers Region of the Northern Territory. These investigations provide a basis for examination of the management implications of environmental change in the wet-dry tropics in general.

5.2.2 The steering committee

A steering committee administered the program over the period 1996–98. It provided focus for environmental monitoring and research on the low-lying coastal plains and wetlands of the Alligator Rivers Region in general. Membership of the steering committee was drawn from Commonwealth and Territory agencies, State and Territory research and educational institutions, and people with particular interests in environmental management of the Region. Agencies and groups represented at steering committee meetings are listed in table 1.

Table 5.1 Attendees of the Steering Committee Meetings for Coastal Monitoring in the Alligator Rivers Region

Organisation	Representative agency
Commonwealth Government	Australian Institute of Marine Science Bureau of Meteorology CSIRO Division of Wildlife Ecology Environment Australia: Portfolio Marine Group Parks Australia North Environmental Research Institute of the Supervising Scientist
Northern Territory Government	Department of Lands, Planning and Environment Parks and Wildlife Commission of the Northern Territory
Tertiary Research and Educational Institutions	Northern Territory University James Cook University University of Western Australia
Community Groups	Bawinanga Aboriginal Corporation Gagadju Association Mary River Landcare Group Northern Land Council

5.3 Components of the coastal monitoring program

The key components of the coastal monitoring program are the communities of interest, establishment of a policy context for the program, operational systems and implementation processes. Communities of interest are indicated by the willingness of agencies to participate in the Steering Committee, or to make representation through that committee.

5.3.1 Policy setting

Waterman (1998) audited the first phase of the monitoring program: its establishment, the strategic approach adopted by the Steering Committee, and implementation of the data collection and information management components of the program. The policy setting and operational structure of the program were defined in that process. Interrelated aspects of policy context for the coastal monitoring program include factors that interface government policy and practical commitments. In the coastal monitoring program they include nationally and regionally focussed coastal policy and wetlands environmental issues, international conventions and agreement. Other policy components have a regional and local focus. These include national intergovernmental mechanisms, the legislative base, and policy programs and projects delivered at the regional and community level.

These policies are driving mechanisms for action by government agencies. They link commitments and obligations at an international level to on ground activities. In many instances governmental programs and projects provide funding aimed at implementing specific policy agendas. Responses to the driving mechanisms vary across the communities of interest. This is well illustrated by the case studies presented by different Australian State governments as part of an assessment of the vulnerability of the coast to climate change and rise in sea level (Waterman 1996). In the Alligator Rivers Region the interest groups include indigenous people, industrial and commercial enterprises, government agencies, local residents and visitors, as is indicated by membership of the Steering Committee. In this respect, the coastal monitoring program has a wide constituency of interest. Conceptually, at least, it facilitated an integrated approach to management by linking national policy programs and project initiatives to the needs of regional and local communities.

As indicated in the *Kakadu National Park Plan of Management 1998–2003* (Kakadu Board of Management and Parks Australia 1998), improved understanding of the natural variability of environmental change will place local communities in a better position to implement on ground management projects in a more cost effective manner.

5.3.2 Operational processes

The operational system for the coastal monitoring program was identified by Waterman (1998). It incorporates:

- identification of information needs by regional groups and stakeholders with interests in the coastal zone;
- interpretation of the needs in terms of standard operating procedures used by the Environmental Research Institute of the Supervising Scientist to administer the program;
- data acquisition and information management domains, including the Environmental Research Institute of the Supervising Scientist, community groups and research agencies;
- progress reporting through the Environmental Research Institute of the Supervising Scientist and the regional stakeholders;

- provisional dissemination and use of the information in coastal management applications; and
- pathways for independent audits and reviews to ensure that governmental and community requirements from the monitoring process are met.

5.3.3 Implementation

Management of the coastal zone in the Alligator Rivers Region, particularly in the Kakadu National Park, is closely related to wetland management, since the low-lying coastal plains comprise a high proportion of the region's wetlands. Storrs and Finlayson (1997) point out that wetland management can not be done in isolation of catchment or land scale management. This is equally so for the coast, where river mouth dynamics play a major role in flood inundation of the estuarine floodplains and coastal plains (Woodroffe et al 1986, Woodroffe & Mulrennan 1993). It requires appreciation of subtle differences in the hydrologic regime of each river catchment and the implications this has for coastal management.

The range of hydraulic regimes varies from rivers, such as the East Alligator, that debouche from the escarpment directly into estuarine reaches to those flowing through extensive wetlands, as does the Magela and South Alligator. It also requires an understanding of the interaction of stream flow with oceanographic processes, especially with local variation in tidal regime and storm surge conditions. With the exception of work currently undertaken at Tommycut and Sampan Creeks by the Northern Territory Department of Lands, Planning and Environment (DPLE), such detailed information is lacking.

Such information can be incorporated into the management planning process for Kakadu National Park and further across the wet-dry tropics of northern Australia. It can also contribute to national assessment and reporting requirements for State of the Environment and for periodic reappraisal of programs under various national strategies and policies for oceans and coasts, biodiversity, and ecologically sustainable development. Further, Australia has international obligations for reporting under various conventions, for example those for world heritage and wetlands. Information gathered under the monitoring program would contribute to fulfillment of these obligations.

5.4 Accountability

The coastal monitoring program has been functioning for a very short time. Hence, many principles of organisation remain to be formalised, including those relating to accountability of performance. In this respect, Waterman (1998) identified a requirement for the methodology developed for the coastal monitoring program to be fully documented and disseminated. In particular, he recommended that documentation should include a detailed explanation of the operational process used by the Environmental Research Institute of the Supervising Scientist to run the program. Comments made here are intended to be a first step to identification of the mechanisms used to ensure transparency and potential utility of the program.

Despite the brevity of its operation, several levels of accountability are entrained in the operational structure of the coastal monitoring program. They include accountability to:

- The Steering Committee, through achievement of the goals it sets the working groups;
- Regional stakeholders with respect to dissemination and potential use of all information gathered;

- The Environmental Research Institute of the Supervising Scientist, in terms of fulfilling the obligations of its charter to protect the wetland environment, including the coastal zone; and
- Governmental requirements at Territory, National and International levels.

During the operation of the project the Steering Committee has been convened on three occasions. At the first meeting (convened 24 October 1996) members discussed potential values in forming a committee and established broad goals for the working group at the Environmental Research Institute of the Supervising Scientist. Requirements to include monitoring as an integral part of management decisions and to ensure that monitoring projects met management needs were considered. Operational procedures were formalised at the second meeting (convened 14 March 1997). Progress in establishing the monitoring framework, acquisition of the differential Global Positioning System, and project planning were discussed. A third meeting (convened 11 February 1998) was held to report progress and finalise reporting commitments to Environment Australia for funding initiation of the program. In the latter context, an independent review was conducted and reported by Waterman (1998) to fulfil governmental obligations.

Should the project be resourced in future, any further stage of accountability should deal with dissemination of information to the community, and its application to on-ground performance in addition to reporting of progress in the administration and implementation of projects.

5.5 Status of the program

A revised version of the Audit Report for Phase I of the monitoring program (Waterman et al 2000, Paper 10, this volume) is presented as paper 10. It provides a summary of the program and its implementation to date.

Further investigations are planned with individual projects being undertaken and linked within the framework provided. Current projects on remote sensing of wetlands, for example, will provide a base for further monitoring of coastal change. The challenge for the Environmental Research Institute of the Supervising Scientist is to provide and manage an information resource for the assessment and monitoring of environmental change at a variety of scales. This will be encompassed within the administrative structure provided by the recently announced National Centre for Tropical Wetland Research (appendix 1). The Centre is an alliance between the Environmental Research Institute of the Supervising Scientist and three Australian Universities: James Cook University in Townsville, Northern Territory University in Darwin, and the University of Western Australia in Perth.

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Paper 10 Assessment and monitoring of coastal change in the Alligator Rivers Region, northern Australia: A review of initial activities

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Abstract

An audit of the Coastal Monitoring Program administered by the Environmental Research Institute of the Supervising Scientist at Jabiru in the Alligator Rivers Region of northern Australia is reported here. The audit provides an overview of the organisation and function of the program. The overview examines whether work undertaken against the broad aims of the program have been attained. It provides an overview of the structure and direction of the program, indicates priorities for addressing any deficiencies in the monitoring completed and suggests priorities to progress the program.

The audit determined that establishment of the Coastal Monitoring Program is an innovative and difficult project, and that monitoring environmental change with the purpose of documenting the natural variability of the biophysical system is a long-term venture. It also found that a solid framework had been developed for the Coastal Monitoring Program and the links established between policy, operation of the program and implementation of projects at the community level. The framework included formation of a Steering Committee to represent stakeholder interests, development of an information management system and organisation of a monitoring program to examine specific areas of change on the coastal plains. Environmental monitoring ranged from monitoring of changes to the shoreline and channel morphology, through problems related to salinisation of wetlands, to delineation of areas where changes in habitats and biota have been recorded. A clear focus on the provision of information on environmental variability was intended to ensure that the products of the process have wide utility. Further, the model developed is specifically generic for application to other coastal monitoring situations.

Key words: Alligator Rivers Region, Kakadu National Park, coastal monitoring, environmental audit, monitoring framework and program

1 Introduction

An overview of the first phase in establishment of a Coastal Monitoring Program in the Alligator Rivers Region of northern Australia is presented. The review evaluates progress in meeting goals for the Coastal Monitoring Program established at the Environmental Research

Institute of the Supervising Scientist in 1996. Initiation of the project followed an assessment of the vulnerability of wetlands within the Alligator Rivers Region to change in climate and rise in sea level (Bayliss et al 1997). This overview is derived from an audit report of the first phase of the monitoring program (Waterman 1998).

The overview presented here:

- examines whether work undertaken against the broad aims of the first phase of the program had been attained;
- provides an overview of the structure and direction of the program;
- indicates the priorities for addressing any deficiencies from the first phase;
- suggests the priorities for ongoing phases of the program.

The audit was carried out at the Environmental Research Institute of the Supervising Scientist in January 1998 and completed in April the same year. Ongoing contact and updates were obtained on work in-progress. The following material has been structured to give an overview and context for the program before indicating progress in implementing the program and priorities for its next phase.

2 Overview of the program

The Coastal Monitoring Program for the Alligator Rivers Region has been initiated by the Environmental Research Institute of the Supervising Scientist as a long-term project with the mission of:

> providing an environmental variability information system for use by all people with interests in the management of the coastal zone of the wet-dry tropics.

The program commenced in October 1996 for a 12 month period with funding support from the Environment Australia Portfolio Marine Group. Following consultations with the Steering Group (see the introduction to this chapter), the first phase of the program was extended until February 1998.

The program was initiated to further a project originally conducted under the Australian Coastal Vulnerability Case Study. This was a component of the federally funded Commonwealth Coastal Action Plan. The Alligator Rivers Region case study was produced as a Supervising Scientist Report (Bayliss et al 1997). This document was also reproduced on CD-ROM for the Australian Coastal Vulnerability Studies Project (Waterman 1998) as one report in the Climate Change Program. Analysis of the case study and assessment of monitoring needs resulted in a recommendation that coastal monitoring projects should be strategically developed (Bayliss et al 1997). This recommendation led to development and initiation of a Coastal Monitoring Program for the Alligator Rivers Region (Finlayson et al 1998a, Eliot et al 1999). The decision was based on the cultural and natural environmental significance of the Alligator Rivers Region, which includes the Kakadu National Park, and on the expectation that the program would provide useful information for the wet tropics of Australia where similar capability did not exist (Finlayson et al 1998b).

3 Context for the monitoring program

The mission for the Coastal Monitoring Program has been set within the context of the Commonwealth's coastal policy released by the Australian Government in May 1995. One of the initiatives under the coastal policy is the establishment of a coastal monitoring system.

The five objectives of the Commonwealth's coastal monitoring system are to:

1. detect changes and determine the condition of the environment;
2. quantify the levels of natural variability;
3. determine if current and projected use is ecologically sustainable;
4. assess the effectiveness of management policy and practices; and identify new management inputs required to maintain or enhance environmental quality and ecologically sustainable use;
5. provide a baseline for local and regional studies and development.

Three basic requirements of the Commonwealth coastal monitoring system will be met by working towards fulfillment of the mission for the monitoring program, ie the need to:

- ensure that the monitoring program addresses management questions;
- coordinate Commonwealth information collection exercise and monitoring initiatives within the Portfolio and other Commonwealth agencies;
- generate understanding, cooperation and support of the key players in coastal management of the Region through involvement and ownership rather than centralised control.

The aims of the Alligator Rivers Coastal Monitoring Program 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 Alligator Rivers Region, and in the wet-dry tropics of northern Australia 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 low lying coastal areas subject to seasonal 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.

Strategies being used to attain the aims involve:

- establishment of a procedure to determine the coastal environment information needs of regional stakeholders;
- instigation of operating procedures to enable the Environmental Research Institute of the Supervising Scientist to manage efficiently and effectively the day to day activities of personnel, consultants and researchers involved with the Coastal Monitoring Program;
- initiation of research systems that will enable:
  - reporting on changes to environmental conditions;
  - physical and biological monitoring to be implemented in the field;
  - management of the information resulting from all forms of research;
- dissemination of information for use by regional stakeholders in implementing coastal zone management programs and projects;

- provision for ongoing independent review of the effectiveness of the environmental variability information system in meeting the needs of regional stakeholders for integrated coastal zone management.

Achievement of the aims should provide benchmarks from which to measure change in wet-dry tropical environments, both nationally and internationally. The Alligator Rivers Region provides an excellent opportunity to document environmental change because of its cultural, and natural resource significance. Also, the Region has a sound history of applied environmental management research (Bayliss et al 1997). There is a considerable body of material that could be collated and synthesised to provide baseline descriptions of the essential characteristics and attributes of change in this type of environment.

The development of further expertise in monitoring changes to the socio-cultural, physical and biological conditions of the Region are of both national and international significance to the management and understanding of the wet-dry tropics in general (Finlayson et al 1998a,c). In particular, a broad monitoring framework should assist the overall monitoring effort in the Region. It will assist with differentiation of changes due to natural factors from those due to mining and other activities.

4 Outline of the program

The monitoring program is being developed by the Environmental Research Institute of the Supervising Scientist in three phases. The first phase had the specific purpose of providing a georeferencing framework as well as information management and monitoring systems for the program. The second phase entails systematic documentation and monitoring of environmental conditions. During the third phase it is envisaged that the lessons learnt in earlier phases may be extended to programs in other wet-dry tropical areas in Australia and overseas.

Specifically, the aims of the first phase of activities were to:

- establish a survey framework for georeferencing field information collected in the Alligator Rivers Region;
- provide an information management system for storing spatial information;
- collate existing baseline information on coastal change and management;
- report on the environmental conditions of the Alligator Rivers Region;

It is envisaged that the second phase will be divided into three broad components.

- Changes to the coastal floodplains of the Alligator Rivers Region will be monitored using baseline information and the geodetic survey framework established during Phase I of the program. This will include further analysis of head expansion of tidal creeks and a review of the sedimentation and stratigraphic resources.
- Hydrological and meteorological information already collated will be interpreted and a sampling framework devised. Changes to the coastal and estuarine shorelines and mangroves will be investigated using sampling regimes based on ground and imagery techniques comparable with techniques used elsewhere.
- Data collation will continue and be linked to needs for coastal monitoring outside the Region. Local communities adjacent to the Region have been invited to participate in the collation and monitoring exercises. This will be extended to develop the utility of the approach for coastal monitoring across the wet-dry tropics.

During the second phase, mapping of environmental parameters will be achieved by remote sensing technology including satellite imagery and aerial photography. This will be used in conjunction with the information obtained from the differential Global Positioning System. This will extend the spatial information systems available for management of coastal and other natural systems in the Alligator Rivers Region. This capability is essential for monitoring natural variations in environmental conditions and potential impacts due to land use such as mining, pastoralism and tourism.

Activity in the third phase should demonstrate the capability and expertise of the Environmental Research Institute of the Supervising Scientist in coastal and wetland research and monitoring to other client. This phase represents the value added component of the investment made in developing the Coastal Monitoring Program by using the professional and technical resources of the Environmental Research Institute of the Supervising Scientist. Extension activities could be initiated through strategic partnerships and will have full cost recovery. Additionally, information generated in the earlier phases of the program is applicable to other areas and useful for marketing the capabilities of the Environmental Research Institute of the Supervising Scientist.

5 Assessment of the initial activities

Funds for the first phase of the program provided for professional and technical staff and acquisition of dGPS technology. The focus on establishing spatial referencing capability was viewed as essential for continued physical and biological monitoring in the Region. Without this capability, the monitoring could not be undertaken at the scale or accuracy required to document change and provide the resolution necessary to differentiate climate induced change.

A dGPS was purchased to facilitate the development of an accurate georeferencing capability and monitoring framework for the Alligator Rivers Region. A permanent GPS base station was established at Jabiru Airport, immediately adjacent to the Environmental Research Institute of the Supervising Scientist, to increase the accuracy of the dGPS. Its establishment occurred after extensive negotiation between the Environmental Research Institute of the Supervising Scientist and the Australian Surveying and Land Information Group (AUSLIG). The infrastructure enables the Environmental Research Institute of the Supervising Scientist to accurately georeference (or locate) and map geomorphic and biologic features associated with the coastal wetlands of the Alligator Rivers Region. This will be an integral part of the continued monitoring.

Establishment of the georeferencing framework has been successful, although the full capability of the system is still to be determined. Initial project work demonstrated the utility of the system for establishing monitoring stations used to accurately document existing environmental conditions. Thus, the first aim of the first phase of activities has been attained.

An information management system for the monitoring program has been established. The system integrates basic geographic information systems technology and encompasses the management of:

- spatial information gained from aerial photography, satellite imaging and field monitoring data obtained by dGPS;
- bibliographic materials documenting past research and descriptions of environmental conditions;
- reports and publications prepared as output from the program.

The aim is to provide an information management system. From one perspective, it may be argued that this has been achieved. However, the aim should explicitly state that this is an ongoing activity. Hence, the aim should be *to provide and maintain an information management system.* Maintenance of the system is essential for the long-term viability of the program and its development as an effective management tool.

The third aim of the program was *to collate existing baseline information on coastal change and management and provide an initial set of reports on the environmental condition of the Alligator Rivers Region.* Projects have been initiated to achieve the aim. The scope of the projects is outlined in the initial proposal for the establishment of the program. Projects have progressed to varying degrees and a considerable body of information has been produced in the form of individual project reports, an honours dissertation (Cobb 1997) and papers to be published in books and journals. The material assembled to date is listed in annex 1.

Collectively, the output is commendable and it could be argued that the third aim is being achieved. It takes more than a year to compile an environmental baseline for the Region. Hence, implementation of the second phase of activities will continue this aspect of the monitoring program.

6 Geographic context for future activities

The georeferencing framework established through the first phase of the program encompasses the whole of Kakadu National Park, which is a major portion of the Alligator Rivers Region (fig 1). The second phase of monitoring activities will maintain the geographic extent of the georeferencing framework established under Phase I, and where applicable extend it to surrounding areas (fig 1).

Kakadu National Park has immense heritage value and is listed as a World Heritage site for both cultural and natural values (Finlayson & von Oertzen 1996). Its extensive coastal wetlands are also listed as internationally important with the Ramsar Convention (Storrs & Finlayson 1997). The Park is largely Aboriginal land that is leased to the Commonwealth as a national park. It is managed jointly by a Board of Management and Parks Australia North (Kakadu Board of Management and Parks Australia North 1998).

The area to be covered by extending Phase II activities encompasses all drainage systems flowing into the van Diemen Gulf, as well as the waters of the Gulf (fig 1). This extended geographic boundary for the monitoring program is viewed as essential. It incorporates management issues on coastal lands fronting onto van Diemen Gulf (Bayliss et al 1997, Finlayson et al 1998a). These lands are managed either by the Northern Land Council (NLC) on behalf of the Aboriginal people, or under the administration of the Northern Territory Government.

The framework established in the first phase of the program has sufficient utility to be extended in the second to include adjacent floodplain systems falling under different jurisdiction and supporting different land uses. This extension will be conducted through liaison with local community groups and build upon existing collaborative projects concerning wetland monitoring and management (Thurtell et al 1999). The third phase of activities will be continued to establish long term measurement of environmental change. Other wet-dry tropical areas in Australia where 'extension' activities could include the river systems to the west of Darwin, the Kimberleys, and the Gulf of Carpenteria (Finlayson et al 1998b,c). Extension activities could be conducted overseas in Africa and parts of monsoon south east Asia. Already, the Environmental Research Institute of the Supervising Scientist and Wetlands International have received support from the Asia Pacific Network for Global Change to initiate vulnerability assessment of two large Asia-Pacific wetlands (van Dam et al 1999). Also, the Environmental Research Institute of the Supervising Scientist has contributed to a monitoring strategy for the Volga Delta, and wetlands in Ghana (Finlayson et al 2000).

7 Overview of individual components of the program

A framework was developed for the monitoring program following discussions with researchers at the Environmental Research Institute of the Supervising Scientist working to establish new projects. This framework is shown in figure 2. Its key components are the requirements of the communities of interest and the policy context for the Coastal Monitoring Program, as well as the operational systems and their implementation. The components are discussed briefly below.

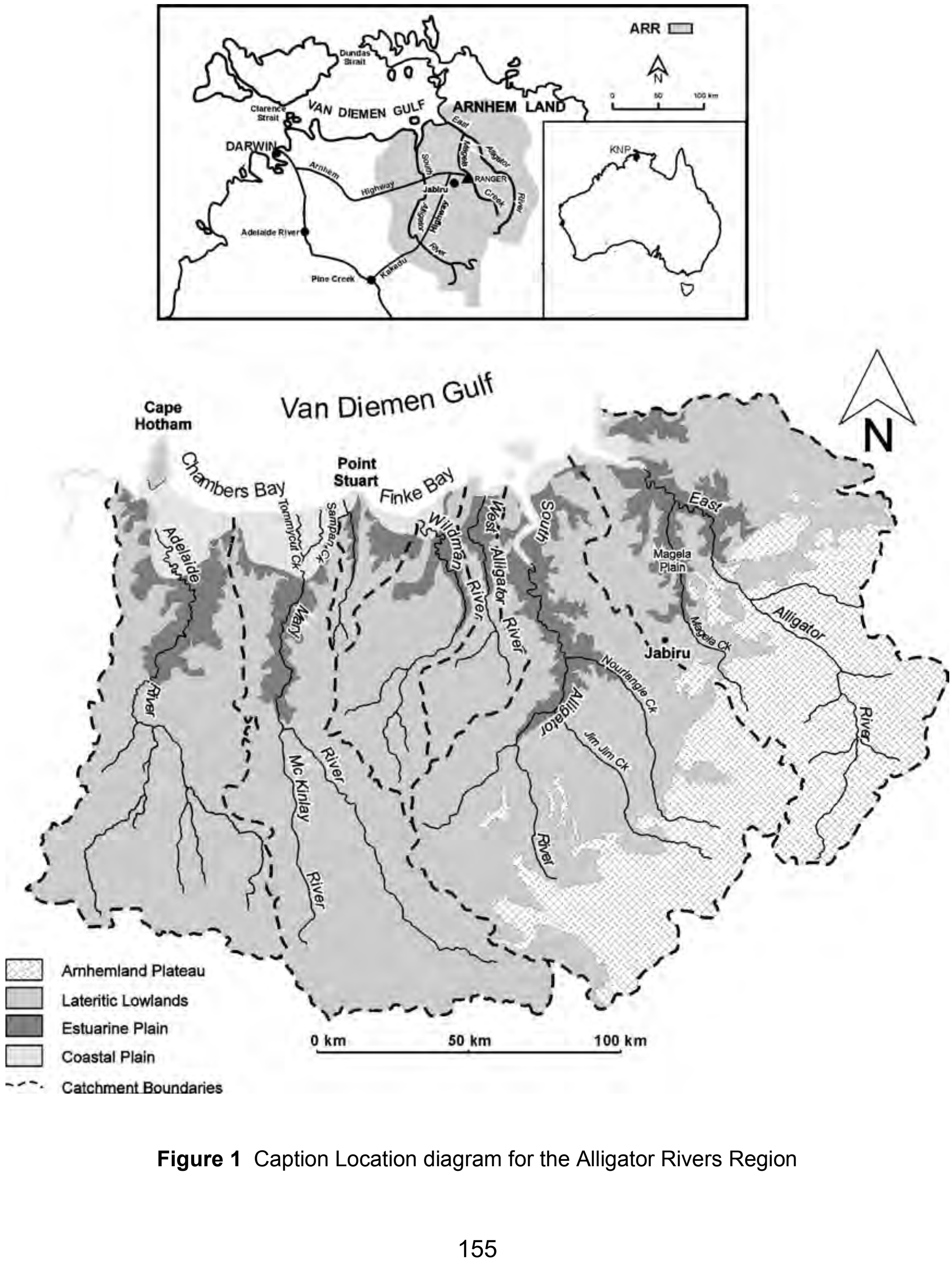

Figure 1 Caption Location diagram for the Alligator Rivers Region

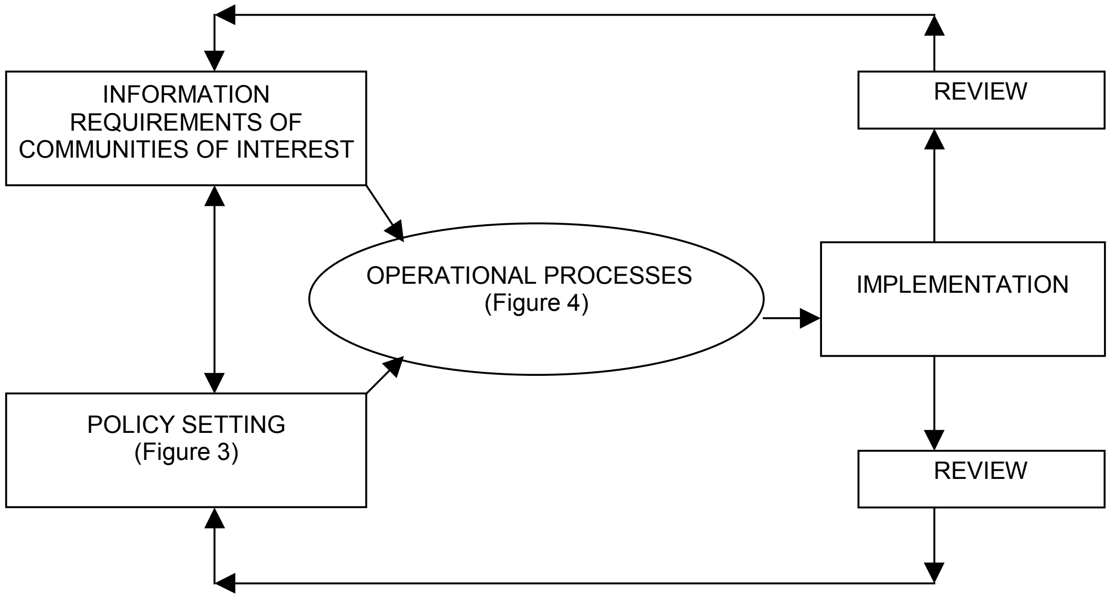

Figure2 Framework for the Coastal Monitoring Program in the Alligator Rivers Region (Waterman 1998)

7.1 Community and governmental involvement

Implementation requires community and government involvement in the Coastal Monitoring Program. Maintenance of their involvement in the application of information generated through monitoring is a major thrust of the systematic approach adapted for the establishment of the monitoring program (Finlayson et al 1998). Core mechanisms for involvement in the monitoring program relate directly to the use of appropriate information for the implementation of on-ground programs and projects to manage components of the coastal environment of wet-dry tropical regions. The tools for initiating this mechanism are training, education and awareness.

The first phase was implemented in Kakadu National Park after consultation with traditional Aboriginal land owners and community representatives identified by Parks Australia North. The framework has been developed with support from The University of Western Australia, Northern Territory University, Bureau of Meteorology, CSIRO, Parks Australia North, Northern Territory Department of Lands, Planning and Environment and the Northern Land Council. Local community and Aboriginal groups (such as the Lower Mary River Landcare Group and the Bawinanga Aboriginal Corporation) were included on the steering group for the first phase of the program. AUSLIG already has provided support.

7.2 Policy setting

Interrelated aspects of the policy context for the Coastal Monitoring Program are outlined in figure 3. Key policy components are the nationally and regionally focussed coastal and wetlands policies, international conventions and agreements. These components are the factors that interface governmental policy and practical commitments. They are implemented through national intergovernmental mechanisms such as the Intergovernmental Agreement of the Environment (Commonwealth of Australia 1992), the legislative base, and policy programs and projects delivered at regional and community levels.

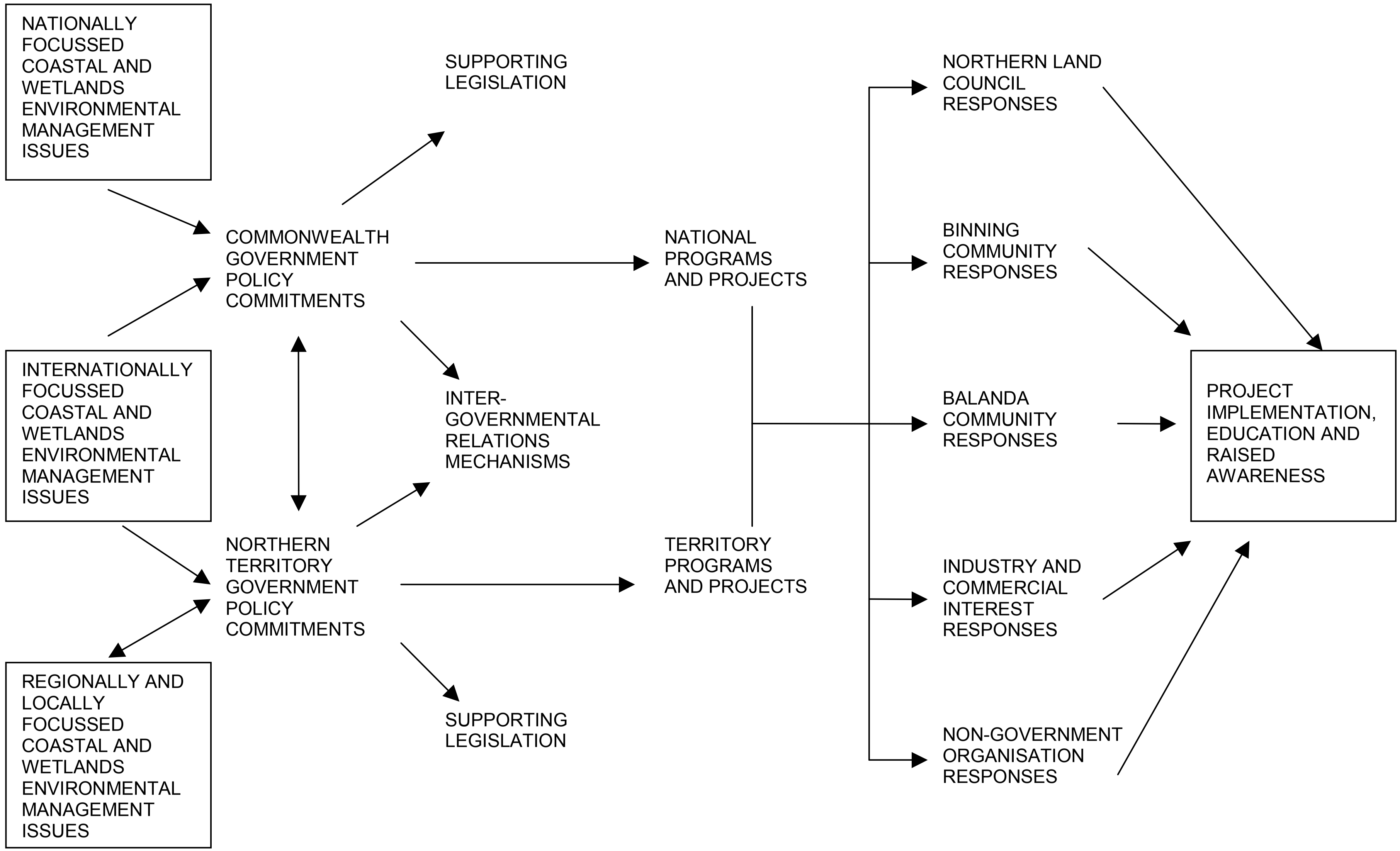

Figure 3 Policy setting for the coastal monitoring program of the Alligator Rivers Region (from Waterman 1998)

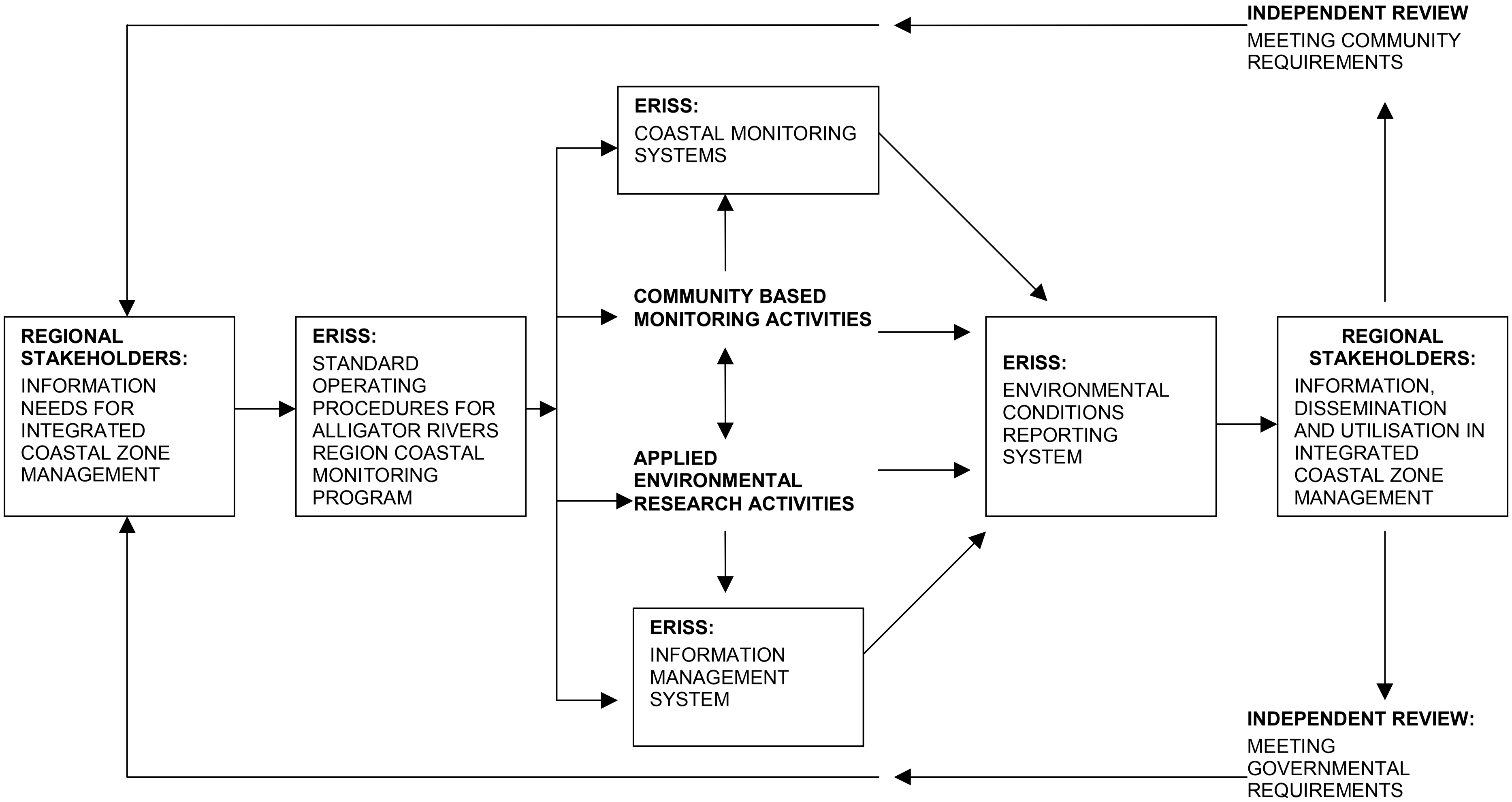

Figure 4 Organisation structure for the Coastal Monitoring Program (after Waterman 1998)

Policy components link commitments and obligations at an international level for on-ground action. These are funded by governmental programs and projects aimed at implementing specific policy agendas related to the coastal environment. Responses to the policy initiatives vary across the communities of interest including indigenous people, industrial and commercial, local residents and visitors. Conceptually, the Coastal Monitoring Program enables an integrated approach linking national policy programs and project initiatives to the needs of regional communities.

Local communities are in a better position to implement on-ground environmental management projects in a more cost effective manner by improving their understanding of the natural variability of coastal systems. Local communities need to appreciate the relationship of their activities to other agendas when undertaking environmental management projects. This is achieved by developing educational materials based on the improved level of local understanding. For example, projects aimed at conserving wetlands and the quality of riverine systems can be linked to international commitments to preserve habitats used by migratory birds or which sustain natural resources in the local area.

7.3 Operational processes

Operational processes within the strategic framework for the monitoring program are summarised in figure 4, and include:

- analysis to determine information needs in relation to research capacities and capabilities;
- guidelines and systems for the establishment of operational processes to generate environmental information;
- the application of environmental information for integrated coastal zone management;
- review processes to ensure that information provided is useable by regional stakeholders.

8 Concluding remarks

Establishment of the Coastal Monitoring Program is innovative and difficult. No other project exists in Australia or overseas on which to model the scope of work planned, the research methodology used and the anticipated outcomes.

Monitoring environmental change with the purpose of documenting the natural variability of the biophysical system is a long-term venture. A high level of scientific rigour is needed to differentiate between natural change and changes due to human or other forcing factors. However, the rigorous approach needs to be tempered with flexibility to allow for adaptation of methods and techniques in the light of the results being obtained. A rigorous yet flexible framework should ensure documentation of existing conditions and the measurement of change. This is required to meet the first aim of the program.

Completion of the first aim is essential to the long term success of the program. Although the other two aims of the first phase of the program have not yet been achieved. Work completed for them has been effective, and the two aims should be considered as ongoing requirements. As stated earlier, the wording of the aims could be taken to mean that the work could be ended at a specific point and progress measured. This is not possible since both relate to ongoing work. Nevertheless the successful commencement of project work for the second and third aims augers well for the success of the second and third phases of the program.

An overview of the program has been completed. A solid framework has been developed for the Coastal Monitoring Program and the links established between policy, operation of the program and implementation of projects at the community level. A clear focus on the provision of information on environmental variability should ensure that products of the process have wide utility. Further, the model developed is specifically generic and applicable to other coastal monitoring situations.

The following priorities should be considered for the next two phases of the program.

1. Methodology developed for formation of the program and its program should be fully documented and disseminated. The documentation should include a detailed explanation of the policy linkages (fig 3) and the operational processes used by the Environmental Research Institute of the Supervising Scientist to establish and run the program (fig 4). Consideration should be given to establishing a website through ERIN and providing access to all relevant electronic publications.
2. Physical and biological monitoring projects identified in documentation for the initial proposal and subsequent papers should be reappraised in light of the results of the first phase of activities. Specifically, in the context of material assembled, key projects with links to readily identifiable changes should be commenced. These should include all facets of the monitoring program, from changes to the shoreline and channel morphology to the delineation of areas where changes in habitats and biota can be recorded.
3. Focus for Dry and Wet seasons should contribute to improving use of the georeferencing tools and assorted information management techniques. These activities will be based on key field projects identified in consultation with stakeholder groups. Special attention should be given to confirm the links these activities have to the overall program; and the utility of potential result for the stakeholders.

The field monitoring program will be supported by the information management system outputs. Those are considered in terms of information on the physical, biological, social, and cultural component of the environment, and are the focus of the environmental variability information system. These outputs need to be documented and presented so that information provides essential input to implementable projects undertaken in the Alligator Rivers Region. A derivative of the output should be papers which can be used as marketing tools for the second phase of the monitoring program. As such, the papers should demonstrate how the research capability developed by the Environmental Research Institute of the Supervising Scientist is transferable to other wet-dry tropical areas.

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