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Predicted climate change, sea-level rise and wetland management in the Australian wet-dry tropics

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Abstract

The vulnerability of coastal areas in the Alligator Rivers Region (northern Australia) to predicted climate change and potential sea level rise was assessed as part of a national study. The coastal area is composed of a number of estuarine and freshwater habitats that are intricately interlinked and can not be effectively managed in isolation of each other. The outcomes of the assessment focused on the floodplain environments of the region, but are also applicable to the broader wetland environments that occur across the northern Australian wet-dry tropics.

The management regime in the region is based on traditional Aboriginal ownership of much of the land, which is leased to the federal government as a national park. Scientific research has been intensive; however, important questions have been raised about the collation and effective use of this information. The vulnerability assessment framework required effective use of this information and cooperation with the management authority to identify change scenarios and management and research responses. A climate change scenario was established as the basis for predicting biophysical change in the coastal and wetland environments. The predictions suggest that large-scale change will occur and many of the existing values derived from these areas (i.e., usage by traditional Aboriginal occupants, and nature conservation) could be degraded or even lost. Recommended management responses include the initiation of specific monitoring, empowerment of local bodies to take active management steps, and to increase awareness of the likely consequences of change. Further data coordination and review are needed to ascertain the validity of the predictions and the concomitant management responses.

Introduction

In 1994 the Australian Federal Government, through the Department of Environment, Sport and Territories (DEST), commissioned eight Australian case studies to assess the vulnerability of coastal land to predicted climate change and potential rise in sea level. The objectives of the project were to:

- establish data requirements for vulnerability analysis;
- determine the adequacy of existing information;
- ascertain the capacity of existing management structures to cope with potential issues devolving from predicted climate change and rise in sea level;
- establish the preparedness of management agencies to confront the issues; and
- identify regional differences in methodology required by management agencies to manage predicted environmental change.

Two case studies were conducted in the Northern Territory; one at Darwin and the other in the Alligator Rivers Region, approximately 150 kms to the east (Figure 1). The case study area in the Alligator Rivers Region, especially Kakadu National Park that lies within its borders, is outlined here (see Bayliss et al., 1998 for a detailed report). The Alligator Rivers Region is isolated and relatively undisturbed. Kakadu, in particular, is of immeasurable value for the world's natural and cultural heritage, and has attracted great

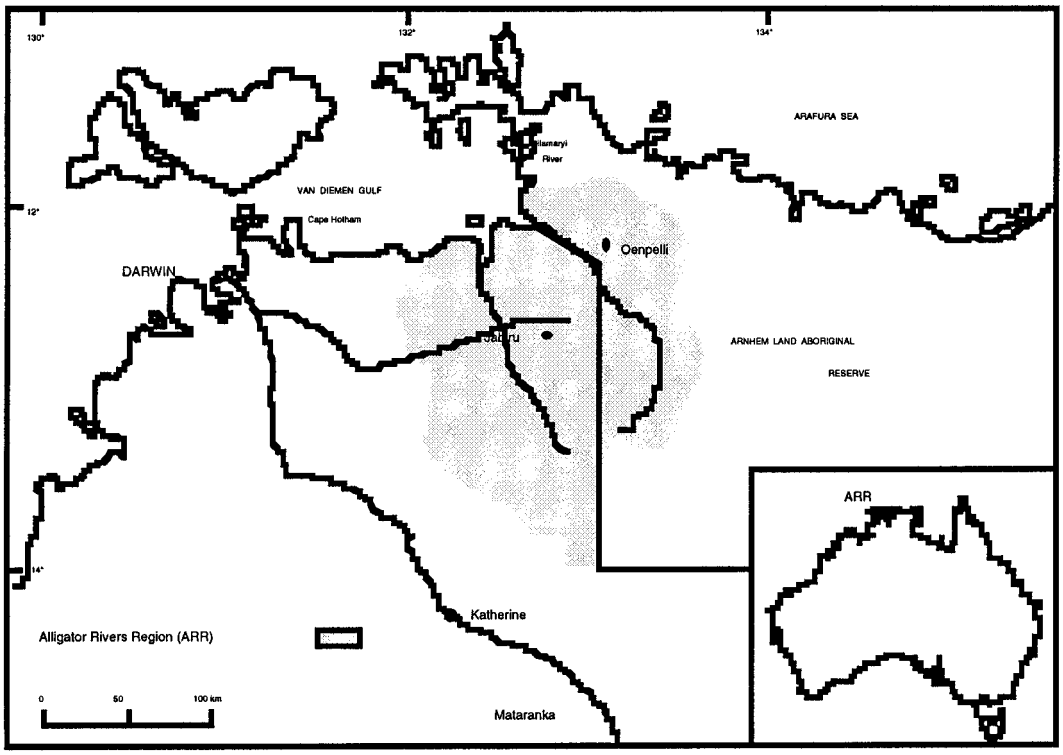

Figure 1. The Alligator Rivers Region and Kakadu National Park.

interest over the past 20 to 30 years (Ovington, 1986; ANPWS, 1991; Finlayson and von Oertzen, 1996a). It includes vast tracts of wetland on floodplains bordering its principal rivers (Finlayson et al., 1990; Finlayson and Woodroffe, 1996). Although the floodplains within Kakadu National Park have been used for grazing in the past, they are now essentially natural areas used for passive recreation and airborne sightseeing (Finlayson and von Oertzen, 1996a). Outside the Park, coastal lands are used for grazing, nature-based tourism, and provide a semi-traditional existence to Aboriginal occupants.

The Alligator Rivers Region, is a highly dynamic environment, physically and biologically (Finlayson and Woodroffe, 1996). It is subject to extreme rates of change due to seasonal and inter-annual variation in climate, storm incidence, tidal fluctuation, and river discharge. Since management has had to take account of this variability its principles and policies may differ from those applied to management of the less variable, temperate environments of the southern coasts of Australia. Management of coastal and wetland areas on the western flank of the Alligator Rivers Region, is vested in the departments of the Northern Territory Government (akin to a provincial or regional government), whereas Kakadu National Park is the responsibility of the Australian Federal Government. Day-to-day management of the Park is the responsibility of Parks Australia North, a conservation agency. The agency acts on behalf of the Australian Government, and in consultation with the Kakadu National Park Board of Management that represents the interests of the Aboriginal people who own much of the land occupied by the Park.

The aim of the vulnerability assessment case study (Bayliss et al., 1998) was to facilitate ongoing assessment of the vulnerability of the Alligator Rivers Region in the context of short-term changes in climate and other environmental factors that occur within planning horizons of approximately 100 years. While the project focused on Kakadu National Park, and the floodplain of Magela Creek, its outcomes have wider application to the management of the Alligator Rivers Region in general, as well as for floodplain environments elsewhere in the Australian wet-dry tropics, and possibly further afield (see Finlayson, 1995).

More specifically, the objectives of this paper are to:

- summarize the findings of the case study of the Alligator Rivers vulnerability assessment project and indicate the physical, biological and cultural implications of potential environmental changes for wet-dry tropical regimes;
- outline the key environmental and management issues identified through the Alligator Rivers case study process; and
- indicate the implications of the impact of climate change on the management of wetlands in the wet-dry tropics.

In this manner we address the critical processes that underlie the probable management responses to environmental change in the wetlands likely to be affected by climate change and sea level rise.

Wetlands of the Alligator River Region

Physical attributes

The Alligator Rivers Region encompasses the catchments of rivers draining into van Diemen Gulf between Point Stuart and the eastern bank of the mouth of the East Alligator River; including the catchments of Love Creek (Bijibiju) and the Wildman, West Alligator (Marangayu), South Alligator and East Alligator Rivers. The region is part of a broader, biophysical region encompassing all of the coastal wetlands from Cape Hotham to the Ilamaryi River on the western flank of the Coburg Peninsula (Thackway and Cresswell, 1995). It lies to the east of Darwin. The Alligator Rivers Region and Kakadu National Park are shown in Figure 1.

Coastal lands of the region are low in elevation, which makes them susceptible to sea level rise. The floodplain wetlands generally lie between 3 and 4 m above Australian Height Datum (Woodroffe et al., 1986). This makes them only 0.2 to 1.2 m above mean high water level. Arguably, a change in climate accompanied by a moderate rise in sea level would substantively affect the physical and biological conditions of the wetlands that constitute the greater part of the coastal plains. In turn, changes to the physical and biological conditions are likely to have cultural, social and economic ramifications and affect the way in which the natural resources of the region are managed. The challenge is to ensure that management recognizes and can cope with such change as a component of its normal operating routine. Thus, we consider that the issues that affect the management responses are as important, if not more, than the actual changes.

Biological attributes

Floodplains in the Region cover approximately 195,000 ha along the major rivers and creeks (ANCA, 1996). Geomorphologically, the wetlands are underlain by riverine muds and are at elevations of less than 5 m. Away from the floodplains, eucalypt woodlands and monsoon forest remnants relate to the higher and laterised lowland surfaces. Remnant monsoon forests also are found on sites of freshwater springs where soil and moisture conditions are conducive to forest growth as well as on chenier ridges on the coastal plain. Freshwater wetlands comprise the seasonally inundated floodplains and include permanent water in an array of lagoons, locally known as billabongs (Hart and McGregor, 1980), and small lakes (Finlayson, 1995). The extremes of seasonal climate have resulted in a diverse flora with characteristically wet and dry season plant communities (Finlayson, 1988; Finlayson et al., 1988, 1989, 1990; Finlayson and Woodroffe, 1996). In the wet season the flowering plants are diverse and profuse, in contrast to the dry season when the vegetation is sparse and less diverse. Overall, the plant communities are highly dynamic and productive (Finlayson, 1991; Finlayson et al., 1993).

Mangroves occur in zoned communities close to the coast and along the tidal reaches of the major rivers. Like the freshwater plants, they are extremely productive (Woodroffe et al., 1988; Finlayson and Woodroffe, 1996). Landward of the mangroves, especially along the coast, there are broad un-vegetated saline flats that are separated from the freshwater wetlands by chenier ridges and low levees. Some 5,000 to 7,000 years ago the mangroves were far more extensive in distribution and may have extended over 80,000 ha in the South Alligator River system (Woodroffe et al., 1985). Over more recent historical time, their distribution has been rapidly changing in association with the incursion of tidal creeks into the freshwater wetlands (Knighton et al., 1991; Woodroffe and Mulrennan, 1993).

Conservation significance

The conservation value of the Alligator Rivers Region has been recognized for some years. The importance of its natural and cultural heritage values is now recognized internationally, and the 20,000 km^2 Kakadu National Park is listed as a UNESCO World Heritage Area. It is the most important natural, cultural, recreational and tourist resource in the region. Further international recognition is given under the

Convention of Wetlands of International Importance, especially as Waterfowl Habitat (Ramsar Convention Bureau, 1990). The wetlands are highly diverse and support large populations of many species, such as waterfowl, fish, reptiles and frogs (Finlayson et al., 1990; Finlayson and Woodroffe, 1996; Storrs and Finlayson, 1997). Further, they are very productive and provide dry season refuge for many species.

Management of Kakadu National Park

Kakadu National Park is largely owned by the Aboriginal people of the area. It is leased by the Commonwealth of Australia and managed by Parks Australia North (PAN) in accordance with policy expressed in the Kakadu National Park Management Plan (ANPWS, 1991).

Uranium is mined within the catchment of Magela Creek, a tributary of the East Alligator River (Finlayson and von Oertzen, 1996a). The mining leases and nearby townsite of Jabiru have been excised from Kakadu National Park. Mining operations and provision of residential and urban services at Jabiru, together with recreational and tourist activities, have direct and indirect effects on the environmental values of the Park. Management of mining, urban and tourist activities is intended to minimize any adverse impacts and maximize the opportunities to conserve the physical, biological and cultural heritage values. This has been pursued through a comprehensive research and monitoring program focused on the channel and floodplains of Magela Creek downstream of the Ranger uranium mine site near Jabiru. The Environmental Research Institute of the Supervising Scientist (ERISS) independently, and in collaboration with other agencies, undertakes and promotes research relevant to the environmental effects of mining operations in the Alligator Rivers Region and minimization of these effects after decommissioning and rehabilitation. Much attention has focussed on the extensive waste rock dumps on the minesite. Although the coastal component of the research has focussed on downstream effects of mining, much of the information gathered is applicable as a baseline to assess the effects of climatic and other changes on the catchment environment (Finlayson et al., 1998a). It also provides a sound basis for comparison with other parts of the region.

Scientific research in the Alligator Rivers Region commenced in the late 1960s and early 1970s with land system surveys (Story et al., 1969, 1976) and an Environmental Fact Finding Study (Christian and Aldrick, 1977). Results of these studies were used in assessment of the impact of mining and milling uranium ore (Fox et al., 1977). Research has continued in the region to gain information for the management of the uranium operations and the National Park. The physical and biological research carried out in the region has been reviewed by a number of authors (Finlayson et al., 1990; East, 1996; Bayliss et al., 1998; Finlayson and von Oertzen, 1996b).

As a consequence of the history of research, information available for the wider region matches the breadth and detail of that for many coastal areas in Australia with a large urban population. However, an important question for management of the Region is whether effective use is being made of the information (Bayliss et al., 1998; Finlayson and Bayliss, 1997). For coastal management to be most effective it is increasingly necessary to ensure dialogue and cooperation between technical, scientific and management bodies, as well as between various government agencies and community groups that share responsibility for management. The ways in which these interest groups are involved in the environmental management process for the region, through management of the National Park and mining operations, may provide a working model for integrated coastal management elsewhere in the remote wet-dry tropics of Australia.

Climate change

In the context of this paper *climate change* refers to trends and fluctuations in climatic factors, such as CO_2 content of the atmosphere, temperature and rainfall (Warwick et al., 1993; IPCC, 1990). These changes occur at time scales up to 100 years and may be irreversible. Changes predicted to occur as a result of the 'greenhouse effect' provide examples of the type of variability to be considered in vulnerability assessment, although other fluctuations in climate may be equally important at this scale. Natural climate variability make it unlikely that changes of the order suggested by global climate models will be confirmed for decades (McQuade et al., 1996). Hence the natural variability of local climatic conditions should be examined as part of the vulnerability assessment process. The natural trends, oscillations and more random perturbations in climate need to be identified and distinguished from more 'exotic' changes caused by human populations.

Table 1. CSIRO (1994) predictions of climate change.

Variable	Prediction
Temperature	Global average warming is anticipated to increase by 0.2–0.5°C per decade, with a best estimate rise of 0.3°C per decade. Australia in 2030, relative to 1990, will be: • 1–2°C warmer in northern coastal areas; • 1–3°C warmer in southern coastal areas; • 2–4°C warmer inland; even warmer in drier areas, and possibly less so in wetter areas.
Rainfall	Rainfall in Australia in 2030, relative to 1990: • large area average increase of 0–20% in summer in the summer rainfall region (NE two-thirds of country); • monsoon more intense but monsoon trough not extending further south; • less certain overall decrease of 0–20% in winter in the winter rainfall region (SW two-thirds of country); • local changes could be two or three times larger due to topographic effects; • general increase in rainfall intensities; • possible marked increase in heavy rain events; • longer dry spells in mid-latitudes.
Extreme events	It is predicted that extreme events will change in magnitude and frequency more rapidly than the averages, e.g., more very hot days, fewer frosts, more floods and Dry spells.
Clouds	CSIRO (1994) note that there is a very preliminary indication of an increase of 0–10% in total cloud cover in tropical Australia and a 0–15% decrease in the south of the continent.
Tropical cyclones	Cyclones could travel further south and their preferred paths may alter but effects on intensity are uncertain. ENSO could affect both the location and frequency.
ENSO	Future behavior of the El Nino Southern Oscillation events is uncertain. Probably El Ninos and anti-El Ninos will continue to occur, to produce drought and flood years.
Winds	Stronger monsoon westerlies are expected in northern Australia and stronger winds will accompany severe weather. Mid-latitude westerlies are expected further south over Australia but change in the trade winds of the north are not yet clear.
Evaporation	It is anticipated that there will be a 5–15% increase in potential evaporation by 2030.
Sea level	Predicted changes in global sea level include: • a global average rise of 3–10 cm per decade; • a best estimate for Australia by 2030 AD is about 20 ± 10 cm above 1990 levels; • local variations due to changes in weather and currents, especially affecting magnitude and frequency of extreme events such as storm surges, waves, and estuarine flooding.
Direct CO_2 effects	The overall effect of increasing CO_2 concentration on water use in a competitive field environment is unknown, although plant water-use efficiency increases in controlled environments. Increased CO_2 concentrations (about 460 ppm, compared to 350 in 1990) significantly increase growth rates of C_3 plants (e.g., wheat and temperate grasses), but have less effect on C_4 plants (e.g., sorghum), This may not necessarily increase commercial yields, due to earlier maturity, climatic stresses, and other effects. Response may be cultivar dependent. Carbon storage is also complex and the subject of further investigation.

Scenarios for climate change and rise in sea level

The major source of information for the prediction of climate change in the Northern Territory has been provided by Wasson (1992) and CSIRO (1994). Their predictions are summarized in Table 1. Unless greenhouse gas emissions are substantially reduced, the cumulative effect of increases in all greenhouse gases is expected to be equivalent to a doubling of pre-industrial concentrations of atmospheric CO_2 (Halpert and Ropelewski, 1993; CSIRO, 1994). Climatic change is likely to be a continuing process from now until well beyond 2030, with superimposed inter-annual variations due to other natural effects such as solar activity and volcanic eruptions. Estimates are

based on the IPCC Scientific Assessment and ongoing CSIRO research.

Sea level changes are related to global climate change (Warwick, 1995); inter-annual variation in weather conditions, such as those related to ENSO events (Komar and Enfield, 1987); as well as to hydro-isostatic (Chappell et al., 1983) and tectonic (Woodroffe et al., 1987) effects within van Diemen Gulf. Two scenarios for global sea level rise have been published. Initially, the IPCC (1990) scenarios were the main source of information for Australia. More recently these have been replaced by the work of Wigley and Raper (1992) which has been adopted by the CSIRO (1994) and provides the basis for vulnerability assessment in the Alligator Rivers Region. Global predictions of sea level rise range from 25 to 80 cm by the year 2100, with a 'best guess' estimate of 50 cm. By the year 2030 sea level is expected to have risen approximately 8 to 30 cm. The estimates are plus or minus 25% lower than the best estimate presented by the IPCC in 1990 (Warwick and Oerlemans, 1990). They require further adjustment to allow for regional and site specific conditions to determine the relative sea level change at that place. Such predictions are not currently available for the Alligator Rivers Region.

Climate and sea level change in the Alligator Rivers Region

Long-term variations in climate and sea level in the region have been established from geomorphologic and stratigraphic investigations from the Mary (Woodroffe and Mulrennan, 1993) and South Alligator River systems (Hope et al., 1985; Woodroffe et al., 1985, 1986), Magela Creek and coastal plains (Nanson et al., 1993; Wasson 1992), and the Point Stuart chenier sequence (Clarke et al., 1979; Lees, 1987). General descriptions of landform evolution have been provided by Story et al. (1969), Christian and Aldrick (1977), Duggan (1985) and East (1996). These investigations provide a context for environmental changes currently occurring in the Region, for the higher frequency changes that have occurred in the past 100 years and which may recur in the near future.

Detailed stratigraphic investigations of the South Alligator River system (Chappell and Grindrod, 1985; Woodroffe et al., 1986, 1987; Wasson, 1992) provide evidence of major sea level and environmental changes in the Region over the past 7,000 years. Their evidence indicates that extensive mangrove swamps were present at a time, 6,500 to 7,000 years ago, when sea levels were up to 1.0 m higher than at present. Subsequent development of river channels and floodplains is considered to have been associated with a slight fall in sea level to its present level 5,000 years ago.

Woodroffe et al., (1986) have compared the characteristics of palaeo-channels in the deltaic-estuarine plains of the South Alligator River with the modern stream. Their results show that the relationship between channel width and distance from the coast was similar, and that past tidal discharges in the sinuous sector of the river were less than today. Since dates from palaeo-channel fills indicate that some of these prior meanders were active less than 1400 years ago (Woodroffe et al., 1986), it is reasonable to conclude than riverine processes have not been significantly different since then.

More recently, short-term fluctuations in sea level, during the historical period, have been examined by the National Tide Facility, Adelaide. The record is short, dating from 1959 to 1992, and based on tide gauge records from Darwin Harbor. It indicates that there may have been a corresponding variation in sea level in the region over the period of record, at rates between approximately –0.17 mm and 0.10 mm per year (Figure 2). However, there is a need for caution in interpreting the short record because the trend is very low. It may be biased by inter-annual variations in climate, such as those due to ENSO events, and it is located outside the Alligator Rivers Region.

The record of annual mean sea levels for Darwin (Figure 2) displays an inter-annual variability rising from approximately 3875 mm to 4125 mm over the years 1972–75, and a relative fall to 1992 levels. The variation reasonably could be anticipated to affect coastal processes and tidal activity within the estuarine reaches of the rivers because of the low gradient of the floodplain. Responses of a sandy beach to sea level fluctuation are of the order of 1.0 m of shoreline retreat for each 1.0 cm of sea level rise (Bruun, 1962, 1983) with the beach response lagging the peak sea level. It is not known whether similar changes are likely to occur on muddy coasts, such as that of the Alligator Rivers Region. Detailed descriptions of short-term variation in climate have not been published and the response rate of coastal and estuarine processes to such change is largely unknown.

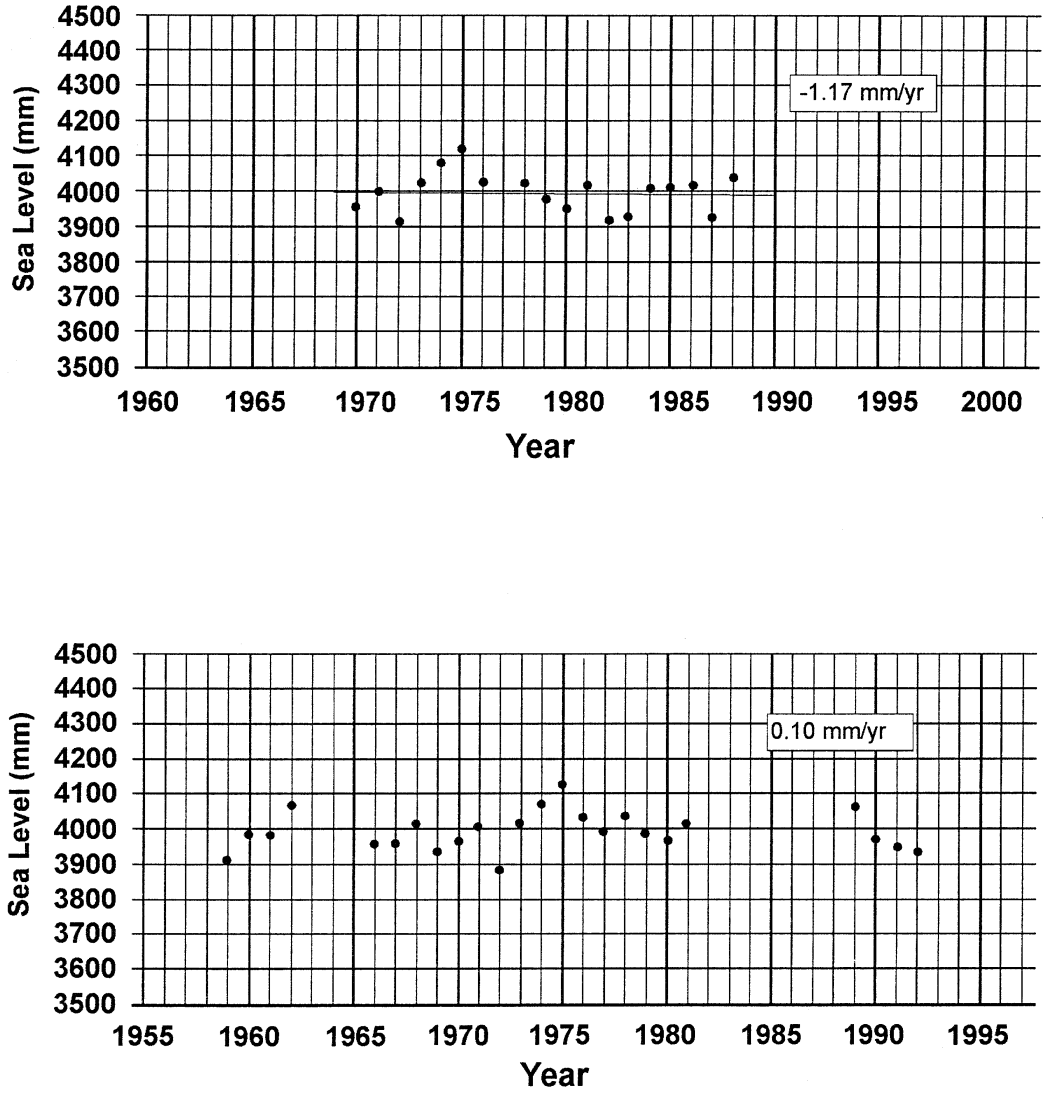

Figure 2. Plots of annual mean sea-levels from two Darwin conventional gauge sites (information supplied by the National Tide Facility, Adelaide, Australia).

Vulnerability assessment

Environmental management in the context of predicted future climate change is a "wicked problem" (Kenchington, 1994) in which management policies must be determined and implemented in a context of uncertainty, ignorance and indeterminacy. In these circumstances, management may be based on the range of environmental changes demonstrably associated with climatic variability and human influences. Such changes are reviewed in the light of available scientific information, current predictions of future climate change and responses suited to the capabilities of the management authorities operating in the region. This approach provides a more holistic procedure and the policy frameworks necessary to maintain long-term sustainabilty of the natural resources and the inherent biodiversity of the region, although the contribution of natural versus exotic processes is not always clear.

The assessment framework

The approach taken in the case study for assessing the vulnerability of the coastal wetland areas of the

Alligator Rivers Region to climatic and other changes was broadly guided by:

- the conclusions drawn from the 1993 IPCC Eastern Hemisphere workshop (McLean and Mimura, 1993);
- recommendations made by the World Coast '93 Conference (IPCC, 1994);
- the findings of Kay and Waterman (1993) and Kay et al., (1995) with regard to the application of the IPCC Common Methodology (IPCC, 1991) to Australian conditions; and
- suggestions made for assessing natural and human induced impacts in the Australian coastal zone in general by DEST (Waterman, 1996) and for the wet-dry topics by Waterman (1995).

It recognizes that changes to the environment of the coastal wetland areas of the Alligator Rivers Region are a product of natural forces and human induced factors (Finlayson and von Oertzen, 1996a). These forces and factors, together with their environmental impact, can be identified and a range of responses determined from first principle.

The assessment framework incorporating the forcing factors, effects and responses is shown in Figure 3. Based on this framework a systematic process was undertaken which covered the following activities:

- Scoping the issues relating to climate and other changes currently affecting the physical, sociological, cultural, social and economic components of the environment of the Alligator Rivers Region, Kakadu National Park and the Magela Creek floodplain.
- Identification of the natural, cultural, social and economic resources of the area which could be affected by climatic and human induced change.
- Description of the biophysical change processes in terms of climatic scenarios, predicted sea level rise, hydrological and hydrodynamic conditions and the geomorphic processes currently affecting the coastal margins, the rivers and the floodplains.
- Assessment of the significance of the changes through review of the possible directions and dimensions of change.
- Determination of the range of responses to natural and human induced change in the Alligator Rivers Region, including strategic and regulatory mechanisms which relate to the management of Kakadu National Park, and the discharge of excess water from a uranium mine onto the Magela floodplain.
- Determination of actions to be implemented in terms of governmental structures and community investment.

Affected areas

Areas that could be affected by climatic and other changes were determined by using a combination of topographic, geomorphologic and biogeographic evidence. Determination of the part of the coastal zone that could be affected by change was done at three scales. These were the biophysical region, the Alligator Rivers Region, and the floodplain of the Magela Creek. Areas that could be affected by climate induced changes at all scales encompass the full length of the shoreline of the region and the floodplains of each of the rivers draining into van Diemen Gulf.

Boundaries of the "impact zones" (Kay and Waterman, 1993) for each of the river floodplains were determined by comparing vegetation patterns at the beginning and end of the dry season. Remotely sensed images were used to identify the zones of maximum inundation and residual water at the end of the dry. The distinct differences between the wetland communities and the eucalypt woodland and monsoon forest patches reflects differences in topography, soil and the underlying geology (Story et al., 1969, 1976).

The Magela Creek floodplain was selected as the specific locality for assessment. It is located within the East Alligator River catchment on the eastern flank of Kakadu National Park (Figure 1), and has been subject to changes as a result of:

- excavations, stockpiles, tailings dam constructions and other infrastructures relating to the mining and milling of uranium ores;
- clearing and accessing for prospecting and mineral exploration;
- development of the town of Jabiru and associated infrastructure to support the mining and tourist activities;
- the provision of road infrastructure to support tourist and recreational activities;
- broadscale clearing for agricultural and pastoral activities;
- seasonal burning as a past pastoral and ongoing land management practice; and
- invasion by pest animals and exotic plant species.

As with the Alligator Rivers Region, the floodplain of the Magela Creek has been subject to considerable research (for example, see reviews by Finlayson et al., 1990; Finlayson and Woodroffe, 1996; Wasson, 1992;

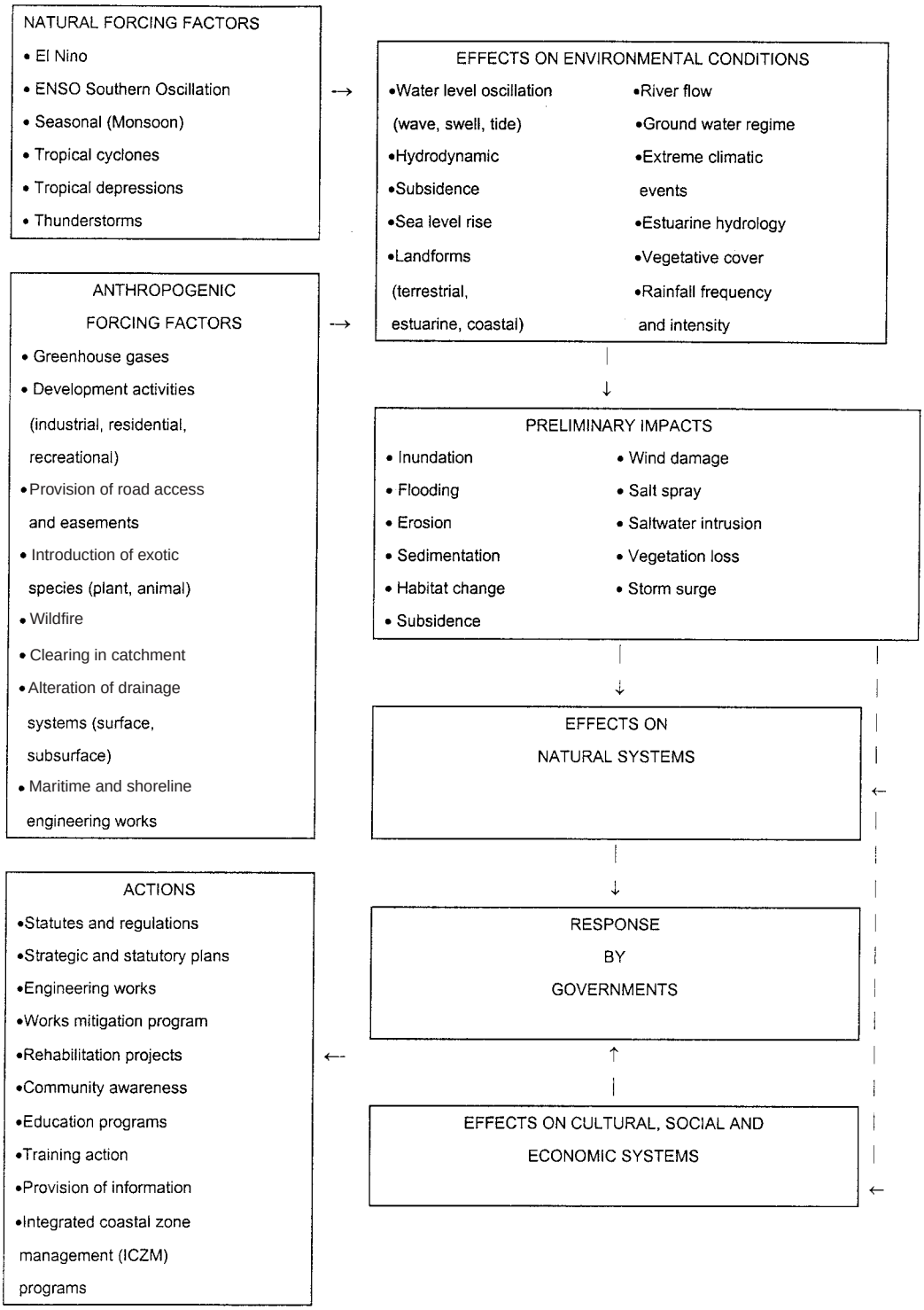

Figure 3. Framework for the assessment of coastal vulnerability in the Alligator Rivers Region, northern Australia (from Bayliss et al., 1998).

East, 1996). The area is viewed as being vulnerable to long-term effects of climatic change as the tailings dam and other mine site features are broken down by acceleration of natural processes because of climate change (Wasson, 1992). Also, the floodplain is vulnerable to saltwater intrusion in response to changes in the fluvial regime of the East Alligator River, as well as to sea level rise and shoreline retreat.

Identification of resources potentially affected

Natural, cultural, social and economic resources across the biophysical region could be affected by climatic and other changes. Specifically, sea level rise, shoreline erosion and saltwater intrusion would combine to remove both the salt and freshwater wetland resources. This would be manifest in:

- reduction or loss of some components of the mangrove fringe on the coast line;
- extensive loss of *Melaleuca* (paperbark trees) stands on the margins of some wetlands;
- colonization of mangrove species along creek lines as an accompaniment to salt water intrusion; and
- replacement of freshwater wetlands with saline mudflats.

Changes in the wetland communities and habitats will result in changes in animal populations, especially changes to the community composition and distribution of bird species found in the freshwater wetlands. Additionally, there would be changes in morphology of the streams and billabongs and in the composition of the fish and other aquatic species. However, detailed analyses of habitat-species interactions have not been done. Changes in the natural vegetation and faunal resources may have cultural, social and economic consequences for the Aboriginal and non-Aboriginal people living in or visiting the area. The cultural resources have both social and economic resource values as they relate to the plants and animals used by the local Aboriginal people. In turn, it is these resources that give social and economic importance to Kakadu National Park as a site of natural and cultural heritage importance to all people.

The cultural, social and economic resources that could be affected by any acceleration of the change process that are discussed in this paper should be viewed as indicative of the breadth of factors to be considered, rather than exhaustive. Nonetheless, it serves to indicate the extent of possible changes to the resources of the Region.

Assessing the significance of potential change

There is a very substantial body of information describing geologic and especially, recent historical changes to the coast and wetlands of the Alligator Rivers Region (Wasson, 1992; Woodroffe and Mulrennan, 1993; East, 1996; Skeat et al., 1996). Oceanographic processes in van Diemen Gulf contribute to many of the changes and are manifested by very high rates of shoreline erosion, changing tidal regimes within the river systems, and contribution to saltwater intrusion into freshwater ecosystems. Changes resulting from these processes are seen in reduction of the fringing mangroves along the shores of the Alligator Rivers Region of the Gulf, expansion of the samphire and saltflat areas, colonization 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 shoreline of the Alligator Rivers Region.

Development of the coastal plains also rests on a balance between these processes such that the coast progrades when sea levels are lowering, rainfall is high and fluvial forces prevail. Conversely, the shoreline retreats and tidal creeks extend landwards when sea level is rising, rainfall is low and coastal processes prevail. There is a wide range of interactions and responses between these extreme conditions. Hence an understanding of the coastal hydrodynamics, and particularly the hydrology of streams and wetlands, is a fundamental requirement for understanding the biological and chemical processes that characterize stream and wetland ecosystems. The complexities of the hydrological cycle for the Alligator Rivers Region are not thoroughly understood, especially in relation to groundwater interactions with the aquatic and wetland ecosystems. Effective management practices for such aquatic ecosystems are often limited by an inadequate understanding of the underlying hydrological processes. Although the Kakadu wetlands have undergone major ecological change over the past few decades (Finlayson, 1991; Finlayson et al., 1988) and controversy still surrounds plans by mining companies in the region to release excess runoff water to the aquatic ecosystems (Johnston, 1991) the com-

plex hydrology of the region has not been adequately investigated.

On the basis of the evidence presented by Woodroffe et al. (1987) and Woodroffe and Mulrennan (1992), it is reasonable to conclude that the tidal creek extension and dieback of *Melaleuca* spp. through saltwater intrusion is partially a consequence of long-term rise of high tide levels. Wasson (1992) notes that if sea level rises sufficiently to re-establish tidal connections between the downstream floodplain and the central high of the Magela Creek system then it is likely that the upstream sections of the plain will be more poorly drained. The period of inundation would probably increase with the aid of a longer wet season. Under these conditions, aquatic macrophytes would probably become more common.

Pastoralists farming lands next to the Alligator Rivers Region have registered concerns over increasing encroachment of saline waters into freshwater wetlands that are used for seasonal pastures (Knighton et al., 1991, 1992; Woodroffe and Mulrennan, 1993). Remedial measures to deal with this problem have included emplacement of open mesh rubble mattresses and earth bunds to impede tide water penetration. The porosity of the mattresses and inherent instability of the bund walls brings these mitigation measures into question. Elsewhere, earth bunds have been used to some effect. More successful approaches to the problem will require an increased understanding of coastal and floodplain hydrodynamics and geomorphology that is based on rigorous, scientific research (Sessional Committee on the Environment, 1995).

Ecological processes affected by environmental change include the expansion and contraction of plant communities with consequent effects on animal habitats. Again, insufficient knowledge of the interaction between wetland plant communities and changes in hydrological and depositional conditions makes prediction of the long-term effects difficult. Wetland plant communities are viewed as being widespread in the region and highly dynamic in terms of variability in species composition, structure of the community and geographic spatial extent. The plant species are widespread at pan-regional and regional scales and no communities or individual species of rare or endangered species have been recorded. Similarly, animal species are widespread and no rare and endangered species are known from areas that could be affected by environmental change.

Management of a changing environment

A major problem for management is whether it has the capability to assimilate change without necessitating major restructuring, extensive re-skilling of staff and loss of corporate memory. In a rapidly changing environment, where sustainable use of resources becomes a critical consideration, loss of fundamental information about change is highly liable to result in a decline of management capability. In this context it is relevant to examine the issues and opportunities that may drive management, the governmental and structural frameworks in which management is undertaken, the organization of information required for its operation, and the roles and responsibilities of participatory groups.

Management Issues and Opportunities

Six broad environmental management issues were identified through the issue scoping process used for the vulnerability assessment. Many of the issues are common to the coastal margins of the wet-dry tropics and underlie the possible management responses required to address the expected extent of ecological change in the wetlands. The areas of issue and their implications are described below.

1. Perceptions and values

There has been no systematic examination of perceptions and values with respect to management of the Alligator Rivers Region. However, societal perceptions and values are manifest in the level of awareness of the possible effects of climatic and associated changes, as well as in attitudes held with regard to the hazards and threats to the environment resulting from climate change. Raising awareness of the implications of climate change is a most important first step in changing governmental and community perceptions of the implications of climate change for environmental resource management. Raised awareness is essential when it comes to government allocation of resources and to alteration of administrative arrangements that will be necessary to address the consequences of climate change.

2. Hazard and risk

Natural hazards of the Alligator Rivers Region include extreme weather events – tropical cyclones, tropical depressions, heavy rainfall, extended wet seasons, excessively high temperatures and prolonged droughts;

flooding, channel avulsion and bank erosion; inundation of coastal plains by storm surge; and coastal erosion, shoreline retreat, chenier migration and saltwater intrusion. Questions of responsibility and accountability may need to be addressed when changes due to particular hazards disrupt orderly use of coastal resources for habitation, industry and commerce, recreation and conservation.

There is considerable evidence of contemporary change throughout the Alligator Rivers Region and neighboring catchments that demonstrates that the coastal wetlands are undergoing very substantial alteration due to shoreline retreat (Woodroffe and Mulrennan, 1993), changing estuarine hydrodynamics (D. Williams, pers. comm.), and saltwater intrusion (Woodroffe and Mulrennan, 1993). Additionally, changes to the level, frequency, persistence and extent of wetland inundation are expected to accompany the predicted 20% increase in summer rainfall. This is likely to extend conditions conducive to the breeding of mosquitoes and other insects that may host infectious diseases and hence affect the health of resident communities and recreational visitors.

3. Governance

Governance in the Region and neighboring catchments is currently not geared to deal with environmental change of the type and magnitude that is currently occurring. Issues are dealt with on a sectoral basis rather than in an integrated, intergovernmental and cross-sectoral manner (Finlayson et al., 1998b). Change is manifest across the biophysical region irrespective of jurisdictional boundaries. Governmental structures and community based management mechanisms must be developed that provide a consistent and appropriate response for system management, rather than simply addressing problems at a sectoral level.

Issues of governance within the biophysical region that includes the Alligator Rivers Region are a microcosm of conditions found elsewhere in Australia. Problems of coordination and integration are common, as are issues relating to relations between government and the wider community, particularly with regard to the development and implementation of management plans. There is a notable lack of formal mechanisms to adequately integrate the roles of the various stakeholders in environmental management. Mechanisms are required because there is a need for effective governmental relations in order that the responses to environmental change are owned and implemented by all concerned. These problems need to be systematically examined and rectified.

4. Strategic management

Strategic management has two interrelated components, regional development and resource conservation. The latter encompasses natural as well as cultural resources. Regional development can not be viewed in isolation from resource conservation because development of the region in social and economic terms is based on the natural and cultural resources. The need to blend regional development and resource conservation may be obvious, but it is an extremely difficult task.

Regional development has strong economic connotations and raises questions about the best use of wetland areas. For example, the areas on the western flank of Kakadu National Park are considered as important areas for seasonal pastures and measures have been proposed to prevent saltwater intrusion (Woodroffe and Mulrennan, 1993). In contrast, representatives from the fishing industry consider that the wetlands need to be retained as natural systems that support recruitment of commercial fish species (Julius, 1996). There is clearly a need for the broad community to resolve such conflict within the context of a regional development strategy. Such a strategy will need to accommodate potentially conflicting objectives of resource development and resource conservation.

Resource conservation must be viewed in a wider regional context when the potential for climate change is taken into account. Specifically, there is a need to consider what the possible loss of freshwater ecosystems might mean for the conservation of aquatic birds, and whether the areas remaining as freshwater systems will sustain bird populations at or near current levels. The implications of this are important when considering what value is placed on water birds as a tourist attraction, and hence as a generator of income for the region, the Northern Territory and the Nation. It raises questions of the adequacy of the conservation estate in its biophysical regional context.

At the time of writing, cost benefit analyses have not been developed for placing a monetary value on natural resource areas and the conservation estate. An economic value needs to be placed on the natural resources to be conserved at least the equivalent level to that placed on the exploitable natural resources.

5. Acquisition and custodianship of information

Inquiries into coastal management have repeatedly found that there are serious deficiencies in knowledge available for management of coastal resources (DEST, 1995). Further, there are serious problems for access to information by managers working in coastal environments. It is hardly surprising then that acquisition and custodianship of information has been recognized as a key issue within the Alligator Rivers Region (Finlayson and Bayliss, 1998). It is likely to impinge on:

- the strategic management of the responses to climate and other environmental change;
- research and monitoring needed to document the processes of change; and
- evaluation of the effectiveness of any management measures taken. Lack of appropriate data and information causes poor decision-making and contributes to inappropriate management of coastal resources. An investment must be made in data and information with the object of reducing uncertainty, improving decision making, enhancing management capability and ensuring that unnecessary funds are not spent on ill conceived and poorly researched projects aimed at remedying environmental change.

A wide range of specific questions arise under this area of issue. They include:

- the value of existing and future data sources;
- accessing of data sources; and
- custodianship of data and information pertinent to climatic and other environmental change (Institution of Engineers Australia 1993).

Coordination of data and information acquisition has been identified as a key component of information management. The need to immediately develop a meta-database is seen as being paramount for the information management process.

6. Environmental research and monitoring

Ongoing environmental research and monitoring is required in the Alligator Rivers Region to provide data and information for:

- further understanding of the processes and extent of environmental change;
- development of management strategies and action plans;
- implementing management prescriptions;
- auditing the effectiveness of management actions; and
- assessing performance of the overall management processes.

Research and monitoring should be broad in scope and include examination of social science questions. The latter would include measures to raise the general level of awareness of natural variation in the environment of the Alligator Rivers Region. Natural systems research is needed to document the processes of change and their effects on the biophysical environment. Both areas of research endeavor will require a high level of innovation to integrate the cultural implications of change for all people in the region.

Monitoring of ecological change in wetlands can be undertaken at several levels and with vastly different techniques. Satellite imagery, often linked to a geographic information system, aerial photography, flora and fauna surveys at the species and community levels, physico-chemical analyses, ecotoxicological testing, and biomonitoring in stream and bankside all have particular advantages and disadvantages. These have been reviewed by Finlayson (1994) and Finlayson et al. (1998a). The choice of technique is dependent on the objectives of the monitoring program and the nature of the site.

Requirements for Management

The IPCC (1990) identified three principles of coastal management to be applied under conditions of sea level rise. They are to:

- avoid development in areas that are vulnerable to inundation;
- ensure that critical natural systems continue to function naturally; and
- protect human lives, essential properties and economic activities.

These principles are applicable in the broader context of environmental change but their interpretation requires more detailed consideration of local factors and processes affecting environmental well being.

Parks Australia North has established mechanisms for the preparation and provision of new management plans for Kakadu National Park (ANPWS, 1991). These entail calling on the wider community for submissions on the manner in which the Park should be managed in future, as well as holding extensive consultations with the Aboriginal people and their representative associations. There is no equivalent mechanism for dealing with the management of coastal wetland areas abutting the western flank of the Park, although a voluntary community-based group

has been established (O'Brien et al., 1996) and integrated catchment management is being implemented. Management of the wetlands east of Kakadu National Park rests with a statutory government authority (the Northern Land Council) and local Aboriginal associations.

Institutional arrangements will need to be developed to meet the governmental and community requirements for integrated management of the coastal wetlands. Current arrangements tend to focus on the specific issues confronting individual agencies or departments within a specific sphere of government. The intra- and intergovernmental dimensions of the issues identified for the coastal wetlands require a more innovative approach because of the scale of the problems, and because they cross-jurisdictional boundaries. New institutional arrangements should include all three spheres of government, the Aboriginal associations, and industry and community representatives. Resolution of the issues will require flexible and dynamic processes that are appropriate to the geographic diversity of the region, the jurisdictional arrangements, and the cultural context.

Roles and Responsibilities

There is a need to develop experience and expertise in managing remote areas that are markedly affected by natural and human-induced processes. Natural changes are those resulting from continuing fluctuation in the frequency and intensity of atmospheric, terrestrial and marine processes; such as inter-annual variation in weather conditions, river discharge and tidal action. All can be modified by deliberate or inadvertent intervention by people. Induced processes in remote areas arise from uncontrolled access to sensitive places, infestation of weeds, fire damage and the introduction of feral animals.

Rateable resources to support environmental management in remote areas either provide a low level of funds to government or are non-existent. Despite this deficiency, there is commonly a large demand by non-residential populations for access to coastal resources in remote areas. As a result there is a requirement for management of these areas to ensure resource sustainability and to minimize environmental degradation. This requirement cannot be met by communities in remote locations, be they Aboriginal or non-Aboriginal communities. For many coastal areas, a compromise solution has been for central governments at all levels to work in partnership with the local communities.

Management in Kakadu National Park is achieved through provision of Australian Government resources. This is necessary to ensure a more holistic approach to the style of management adopted and that the resource base is scientifically monitored for sustainable economic use of the region. At present, the Australian Government resources are not generally available to communities in the wider Alligator Rivers Region or adjacent catchments. Hence there is scope for the Australian Government to integrate its resources with those of the Northern Territory Government and the wider community.

Management responses from the vulnerability assessment provide a framework for:

- ongoing evaluation of the significance of changes to the natural and human systems of Kakadu National Park and the floodplain of Magela Creek. This process will take a more holistic approach and use resources from within and outside the region.
- long-term integrated management of the Alligator Rivers Region in terms of control and organization arrangements, management plans, implementation mechanisms and community involvement.
- monitoring programs which encompass baseline and reference stations to produce data and information which can be used immediately in the management process by relevant agencies and associations and the people who reside in and use the Park. This would include both processes for data and information management (spatial, textual, numerical) as well as mechanisms for the dissemination of intelligence (or knowledge) which document the rate, effects, and implications of change.
- auditing the management processes needed to deal with environmental change in the Alligator Rivers Region. This could include management reviews as well as independent compliance auditing. Auditing is viewed as an extension of the monitoring process. It is intended to evaluate the effectiveness of management procedures being used as well as assess the achievement of performance objectives set within management plans and monitoring programs.

Management options

The Australian Government has recognized that all three spheres of government and the local community must be involved in the management process for it to

function effectively. The (Australian) Commonwealth Coastal Policy is the basis for *putting the Commonwealth's house in order* (DEST, 1995). A lack of integration across sectoral interests within government has repeatedly been identified as a cause for great concern about the effectiveness of coastal management. The number of agencies with sectoral management responsibilities that affect the coast and the unclear boundaries of responsibilities contributes to this lack of integration (Resource Assessment Commission, 1994). The Australian Government view is that the best way to achieve integration of programs affecting the coastal zone is for agencies and authorities to retain existing responsibilities while increasing coordination between them. This ensures that programs and policies share a common goal and meet government objectives for use of the coastal zone (DEST, 1995).

Integrated environmental management is essential for the Alligator Rivers Region because of the range of Australian Government sectoral interests. These include Environment Australia – PAN and ERISS, the Australian Heritage Commission, Bureau of Meteorology and CSIRO. If the various departments and agencies, several from the same portfolio, can't coordinate their activities in the coastal zone of the region there is very little hope that integrated coastal management can be achieved at an intergovernmental level elsewhere.

Organizational Arrangements

Control of the management processes for Kakadu National Park is derived from the (Australian) Commonwealth National Parks and Wildlife Act, 1975, as detailed in Kakadu National Park Plan of Management (ANPWS, 1991). They encompass the mechanisms for controlling activities in the mine lease areas and the town of Jabiru. There are no administrative or organizational arrangements that are specific to coastal wetland areas within the Park (Finlayson et al., 1998b). Elsewhere in the Alligator Rivers Region it is more difficult to specifically prescribe a statutory basis for control. For management to be integrated at a regional level there will need to be specific control mechanisms established through intergovernmental agreement and with landowners.

Integrated catchment management is being implemented for the Mary River to the west of the Park. A catchment management committee has been established that brings together government, conservation, pastoral, fishing and community interests. There is no similar organizational means of dealing with management of those parts of the East Alligator River not within the Park. A voluntary community group operates in the catchment of the Mary. No similar group operates on the eastern flank of the Park.

Coastal and Catchment Management Plans

In its coastal policy statement the Australian Government identified a number of areas on which attention should be focused to improve coastal management. These include:

- increased local community participation in coastal management;
- provision of integrated solutions to particular management issues;
- increased capacity and knowledge of those with coastal management responsibilities to enable them to be discharged effectively; and
- development of appropriate links with regional neighbors.

The most appropriate mechanism for their application in the Alligator Rivers Region is through the preparation and implementation of specific coastal and catchment management plans. For Kakadu National Park, these plans could be prepared as an integral part of the revised Plan of Management. Further, a coast and catchment plan could be prepared for each of the rivers within the region. Such plans could be developed cooperatively with the jurisdictions responsible for those parts of the East Alligator and Wildman Rivers outside the Park as a function of the task.

Government and community involvement in the implementation of coastal and catchment management plans should be as broad as practicable. Resources provided for implementation should be allocated with full awareness of the multi-faceted nature of the management processes needed to deal with the maintenance of the conservation and economic values of the area as well as for the long-term sustainability of the greater region within the context of environmental change.

Mechanisms will be required within the regional strategic planning, and coast and catchment planning, processes that will accommodate the consultative processes used by Aboriginal people. Consultation mechanisms should be used that can cater for the small and dispersed regional population. The use of electronic communication systems should be fostered. Existing technical committees provide part of the mechanisms.

However, these are generally directed towards technical planning and advice and may not be appropriate for the broader community. Yet, it is the involvement of the entire local community that is essential if local community responsibility and empowerment are to succeed.

Conclusions

Responses to changes arising from the effects of natural and human forcing factors on the environmental conditions of the Alligator Rivers Region and Kakadu National Park require focus on actions that can be taken by the Australian Government as well as the Park's residents. For the wider bio-region, focus needs to be on a range of possible actions including the following:

1. Enhancing the research and monitoring capability in the region to make timely input into the management process for Kakadu National Park. This will entail the installation of new monitoring stations and the re-establishment of selected hydrological and climatic monitoring stations used in the past. Additionally, it will entail instituting quantitative measurements of past changes as well as monitoring programs to document changes to the shoreline, river and creek systems as well as the vegetation communities and faunal habitats of the wetlands.
2. Clearly delineating strategic and regulatory responsibilities to enable relevant organizations to effectively cooperate and contribute to the long-term management of Kakadu National Park, in general, and the Magela floodplain, in particular. Special attention will need to be given to components of the ecosystem, such as the freshwater plant communities, that may be affected by the change processes.
3. Improving the capacities of governments and communities that will be affected by coastal change so that they can understand the significance of the natural variability inherent in the systems that are changing and to appreciate that change is inevitable. In particular, this means that awareness of change must be maintained and that the attitudes of the communities of interest must become fully attuned to the implications of the change processes. For example, if the freshwater systems of the Alligator Rivers Region are to become saline, then people must understand that the change will bring with it another set of environmental conditions that are not necessarily inferior to those they replace.
4. Empowering and resourcing governmental bodies and community organizations so that they can take an active role in the management process. This will require an integrated approach that would result in the relevant local government agencies, statutory authorities, local associations and commercial enterprises being involved in catchment and coast care programs. Conduits will need to be established to enable those community groups that wish to become part of the management process to be coordinated and resourced.

For the above actions to be of long-term benefit Government will need to provide management structures and procedures that can persist for the responses to be of long-term benefit. Further, the management mechanisms will be required to accommodate the full range of environmental changes (physical, biological, cultural, social, economic) that are occurring. Government must involve the wider community in the direct management and monitoring of the natural, cultural and recreational resources that could be deleteriously affected by climatic and human induced changes for effective implementation of any actions. In other respects the Alligator Rivers Region has always been an environment of awesome change at all scales. In the short timespan of predicted climate change, the landforms may change, biotic communities fluctuate in composition and distribution, and people suffer economic inconvenience, but the beauty of the region will remain for those who have an affinity with the wet-dry tropics.

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