interest must become fully attuned to the implications of the change processes. For example, if the freshwater systems of the ARR 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.

- Empower and resource governmental bodies and community organisations so that they can take an active role in the management process. This will require an integrated approach that would result in the Northern Land Council, the Binninj Associations of the Region, Jabiru Town Council and ERA Ranger uranium mine 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.

Government will need to implement actions that will provide management structures and procedures that can persist for the responses to have long-term benefits. The management mechanisms will also need to accommodate the full range of environmental changes (physical, biological, cultural, social, economic) that are occurring. Further, government must involve the wider community in the direct management and monitoring of the natural, cultural and recreational resources that could be affected by climatic and human induced changes.

The management responses arising from this vulnerability assessment are outlined in Section 6. Overall, they provide a framework for the following:

- The 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.
- The long-term integrated management of the ARR in terms of control and organisation 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 ***eriss***, Parks Australia, the Northern Land Council, and the Binninj and the Balanda 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 ARR. 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.

3.0 Environmental change

Environmental problems in the ARR include the introduction of exotic flora (eg Mimosa pigra and Salvinia molesta) and fauna (eg buffalo, pigs and potentially cane toads), saltwater intrusion into the freshwater wetlands of the coastal plains, and increasing use of the region for tourism. During the past two decades scientific research and monitoring related to these problems, as well as to issues associated with establishment of the ERA Ranger uranium mine, have established a regional capability to assess environmental change as well as providing a significant record of change. Science strongly underpins the management of Kakadu National

Park and, particularly, the catchment of Magela Creek. The extent to which this is true for the remainder of the ARR, and whether management of the wider region might be more holistic, remains open to question.

Titus and Barth (1984) recognised three consequences that are anticipated to result from predicted change in climate and rise in sea level. These are shoreline retreat, saltwater intrusion and increased flooding. They are inter-related through hydrodynamic processes and variation in the coastal sediment budget. Titus and Barth (1984) related saltwater intrusion to land subsidence. All of these may be applicable to the ARR, with saltwater intrusion being particularly significant. All have been examined as part of published research completed in the ARR, although a full determination of the geographic extent of the problems remains to be established. For example, saltwater intrusion in the ARR may also be due to a relative change in sea level, retreat of the shoreline, and other processes.

3.1 Vulnerability

The concept of vulnerability of an ecosystem to the effects of climate change induced by humans has cultural, social, economic and political dimensions that should be acknowledged as the primary factors in vulnerability assessment. In the ARR this is highlighted by some fundamental philosophical differences in attitudes to environmental change between Binninj and Balanda. Over time, generations of Binninj have lived with the consequences of environmental change. In the past their lifestyles have included adjustment to climate change through the late Quaternary geologic period, as well as continuing adjustment to very dramatic, short-term change induced by the Balanda Impost—the arrival of Europeans, their livestock, weeds and diseases. In contrast to this, Balanda and possibly some Binninj in the ARR generally favour retention of a status quo that does not exist in natural systems, but which apparently requires protection of capital invested in property and infrastructure. The principal questions in vulnerability assessment relate to considerations of what environmental changes are likely to have deleterious effects on Kakadu National Park and on people using the region, and whether those changes can be minimised or mitigated without causing other equally serious impacts.

In other respects, vulnerability needs to be operationally defined to suit the purpose for which the assessment is being made. This recognises that there will be basic differences between some environmental components. For example, different types of beaches will vary according to their sediment size, level of exposure to storm conditions and high water levels. Estuarine and freshwater ecosystems will also differ widely in terms of their sensitivity to changes in water level, water quality, flood regime and storm surge inundation. The options that are available to manage changes in the environment need to be developed with an in depth understanding of the different levels of sensitivity to change and the ways in which the cumulative effects of change can be seen in natural systems.

The central problem for vulnerability assessment is to ensure that scientific information, technical solutions and management procedures are strongly interlinked, and that each is fully represented, in developing and implementing responses to environmental change, and in assessing the outcomes of those responses. The dilemma is well illustrated by current management problems on the coastal plain of the Mary River. In this context Woodroffe and Mulrennan (1993) have pointed out that:

> The plains are not stable, but are part of a dynamic and at times rapidly changing system. Management and physical intervention needs to recognise and accommodate this changeability. Tidal wetlands, especially mangroves, though less productive than freshwater wetlands, represent ecologically significant resources, and may act to encapsulate tidal flows. Physical intervention may be necessary where landuse

> changes are unacceptable or to prevent the loss of highly valued resources but should be undertaken within the context of a wetland management strategy and predefined conservation priorities.

In contrast to this, the management strategy recommended by the Sessional Committee on the Environment of the Legislative Assembly of the Northern Territory (1995) is largely technologically based. Its central recommendation was:

> that engineering investigations, environmental assessment and budgetary planning be completed, in conjunction with the pilot works trials, to establish the feasibility of constructing works within the next 2–3 years which will permanently dampen tidal flows through the mouths of Tommycut and Sampan Creeks.

This demonstrates the failure to bring science and management together to resolve one of the most important natural resource management issues being confronted in the coastal wetlands adjacent to the ARR.

3.2 Climate change

Climate is an abstract concept. It represents the summation of all interacting atmospheric processes and weather conditions affecting a locality. The atmosphere is subject to natural variations on all time scales, ranging from minutes to millions of years. However, vulnerability assessment is currently considered in the context of variation in climate that is expected to result, or has resulted, from human interference with atmospheric processes (Warwick et al 1993; IPCC 1994). The climate changes under consideration in this context commonly refer to trends in climatic factors, such as CO2 content of the atmosphere, temperature and rainfall. These changes occur at time scales up to 100 years and may be irreversible. Changes predicted to occur as a result of the 'greenhouse effect' provide examples of the type of variability to be considered in vulnerability assessment although other fluctuations in climate may be equally important at this scale. Hence the natural variability of local climatic conditions should be examined as part of the vulnerability assessment process. McQuade et al (1996) have pointed out that the masking effects of natural climate variability make it unlikely that changes of the order suggested by global climate models will be confirmed for decades. The natural trends, oscillations and more random perturbations in climate need to be identified and distinguished from the 'exotic' changes caused by human populations. Exotic changes include physical alteration of the shoreline and the introduction of exotic plants and animals.

The major source of information for the prediction of potential climate change in the Northern Territory, and current scientific advice on the regional implications of that change, has been provided by Wasson (1992) and CSIRO (1994). The generalised best estimates and ranges, mainly for the year 2030 AD have been provided by the CSIRO (1994). Unless greenhouse gas emissions are substantially reduced, the cumulative effect of increases in all greenhouse gases is expected to be equivalent to a doubling of pre-industrial concentrations of atmospheric CO_2 (NOAA 1992; CSIRO 1994). Climatic change is likely to be a continuing process from now until well beyond 2030, with superimposed interannual variations due to other natural effects such as solar activity and volcanic eruptions. Estimates are based on the IPCC Scientific Assessment and ongoing CSIRO research. Surprises, including rapid changes, are possible according to these sources. Potential future changes outlined by the CSIRO (1994) are summarised below.

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, eg 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 behaviour of the El Nino − Southern Oscillation events is uncertain. Probably El Ninos and anti-El Ninos will continue to occur, producing 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 is not yet clear.

Evaporation

It is anticipated that there will be a 5−15% increase in potential evaporation by 2030.

Sea level

Predicted changes in global sea level include:

- a global average rise of 3−10 cm per decade;
- a best estimate for Australia by 2030 AD is about 20 $\pm$ 10 cm above 1990 levels;
- local variations due to changes in weather and currents, 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 with 350 in 1990) significantly increase growth rates of C_3 plants (eg wheat and temperate grasses), but have less effect on C_4 plants (eg 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.

3.3 Sea level rise

3.3.1 Predicted future sea level rise

Sea level changes in the region are related to global climate change (Warwick et al 1993); interannual variation in weather conditions, such as those related to ENSO events (Komar & 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. These were replaced by the work of Wigley and Raper (1992) updated in 1995. These have been adopted by the CSIRO (1994) and provide the basis for vulnerability assessment in the ARR. Global predictions of sea level rise range from 25 to 80 cm by the year 2100, with a best estimate of 50 cm. By the year 2030 sea level will have risen between 8 and 30 cm. The estimates are plus or minus 25% lower than the best estimate presented by the IPCC in 1990 (Warwick & Oerlemans 1990). They require further adjustment to allow for regional and site specific conditions to determine the relative sea level change at that place.

3.3.2 The long-term geomorphologic record of sea level change

Long-term variations in climate and sea level, those occurring over hundreds of years to millennia, in the ARR have been established in geomorphologic and stratigraphic investigations. The investigations have been completed for the Mary (Woodroffe & Mulrennan 1993) and South Alligator River systems (Hope et al 1985; Woodroffe et al 1985a, b & c, 1986), the Magela Creek and coastal plains (Nanson et al 1990; Wasson 1992), and the Point Stuart chenier sequence (Clarke et al 1979; Lees 1987). General descriptions of landform evolution in the region have been provided by Storey (1969), Christian and Aldrick (1977) and Duggan (1985). 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 by Chappell and Grindrod (1985), Woodroffe et al (1986, 1987) provide evidence of major sea level and environmental changes in the region over the past 7000 years.

> Radiometric dating evidence from the South Alligator River... suggests that extensive mangrove swamps developed between 6500 and 7000 years ago and flourished for about 1000 years. Pollen analysis of a stratigraphic core at a mid-plains site links the growth of these forests with the interaction of sea level change and sedimentation. This was succeeded by the development of plains with tidal river channels, a dramatic ecological change that has implications for all coastal and nearshore profiles (Woodroffe et al 1987).

The extensive mangrove swamps were present at a time, 6500 to 7000 years ago, when sea levels were up to 1.0 m higher than at present. The development of river channels and floodplains is considered to have been associated with a slight fall in sea level to its present level after 5000 years ago.

Woodroffe et al (1986) have compared the characteristics of palaeochannels 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 palaeochannel 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.

Woodroffe et al (1987) concluded that:

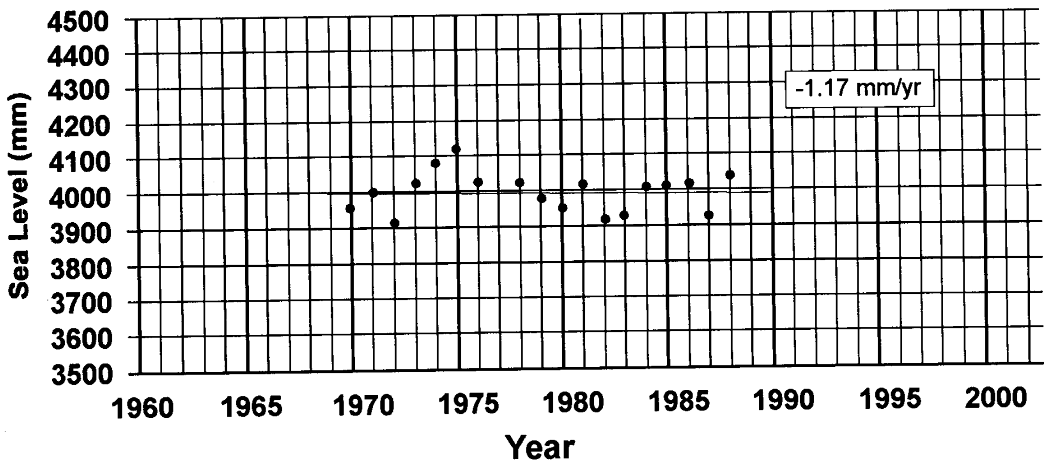
> Initiation of cuspate channel development at the expense of the sinuous river has had significant effects on the modern system. The process involves channel widening and elimination of former sinuous curves, with the more sandy fraction of the eroded sediment lodging in mid-channel shoals. It is unclear whether this widening is initiated by shoaling of the sinuous river, which might occur through progressive accumulation of fluvial sediment, through upstream movement of estuarine sediment by the increasingly asymmetrical tidal flows, or through a combination of both processes, or whether it is caused by bank failure for some other reason. Whatever the cause, the consequence is that tidal levels rise in the upstream direction. Using tidal comparison with the Adelaide River as well as stratigraphic data we conclude that high spring levels have risen by one metre in the Arnhem Highway area since the sinuous river phase.
>
> Progressive rise of high tide levels over the last 2000 years or so places the floodplains at risk of saltwater invasion unless sedimentation keeps pace. The evidence of shell middens ranging back to 4000 BP and showing little sign of burial indicates that sedimentation has been negligible over much of the plains for several thousand years.

On the basis of the evidence presented by Woodroffe et al (1987) and Woodroffe and Mulrennan (1993) 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. Areas of risk are the lower floodplain palaeocreek and palaeochannel environments. 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.

3.3.3 The historical record of sea level fluctuation

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

The record of annual mean sea levels for Darwin (fig 2) displays an interannual variability rising from approximately 3875 mm to 4125 mm over the 4 years from 1972 to 1975, and a relative fall to 1992 levels. The variation reasonably could be anticipated to affect coastal processes and tidal activity within the estuarine reaches of the rivers. However, the response rate of coastal and estuarine processes to such change is largely unknown. Responses of a sandy beach to sea level fluctuation are of the order of 1.0 m of shoreline retreat for each 1.0 cm of sea level rise (Bruun 1962, 1983) with the beach response lagging the peak sea level. Similar changes may be anticipated to occur on muddy coasts.



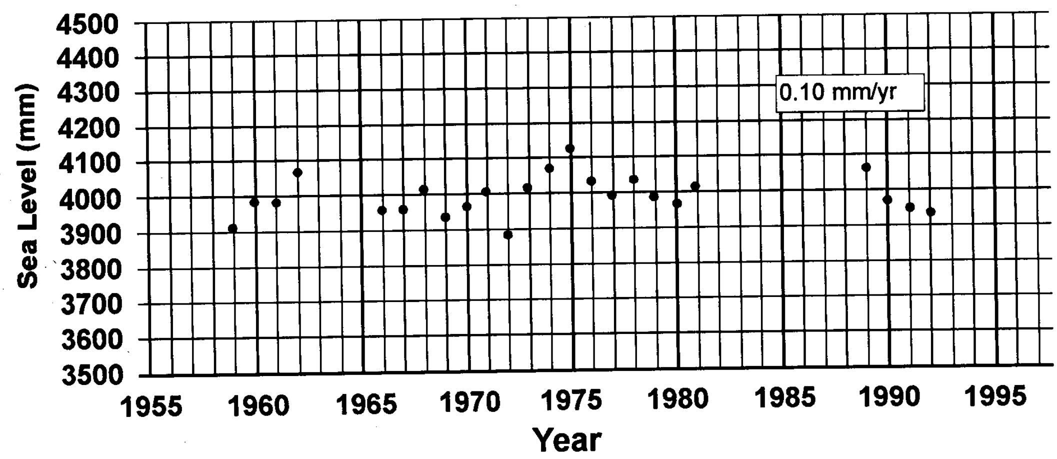


Figure 2 Plots of annual mean sea levels from the two Darwin (conventional) gauge sites (supplied by the National Tidal Facility)

3.4 Environmental responses

Environmental responses to climate and sea level changes are manifested through hydrological, hydrodynamic, geomorphological and ecological processes. Development of the coastal plains also rests on a balance between these processes such that the coast progrades when sea levels are lowering, rainfall is high and fluvial forces prevail. Conversely, the shoreline retreats and tidal creeks extend landwards when sea level is rising, rainfall is low and coastal processes prevail. There is a wide range of interactions and responses between these extreme conditions. Hence, an understanding of the coastal hydrodynamics, and particularly the hydrology of streams and wetlands, is a fundamental requirement for understanding the biological and chemical processes that characterise stream and wetland ecosystems. The complexities of the hydrological cycle for the ARR are not thoroughly understood, especially in relation to groundwater interactions with the aquatic and wetland ecosystems. Effective management practices for such aquatic ecosystems are often limited by an inadequate understanding of the underlying hydrological processes.

Although the Kakadu wetlands have undergone major ecological change over the past few decades (Finlayson et al 1991; Finlayson et al 1988) and controversy still surrounds plans by mining companies in the region to release excess runoff water to the aquatic ecosystem (Johnston 1991), this has not provided sufficient impetus to thoroughly investigate the complex hydrology of the region.

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

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

4.0 Processes of change and resources affected

The biophysical environment is dynamic, continually changing in response to variations in weather and climate. In order to better understand the processes of change the interactions between physical and biological processes are perceived in relation to the resources affected. Likewise, the cultural and social components of the environment are dynamic and also respond to the biophysical changes. These complex sets of process and resource interactions are discussed in the context of environmental changes in the ARR.