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Saltwater intrusion and mangrove encroachment of coastal wetlands in the Alligator Rivers Region, Northern Territory, Australia

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Australian Government
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Executive summary

The aim of 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 in Northern Australia, and link the findings to similar surveys of the western Gulf. This required examination of the tidal creek networks to identify their network patterns and growth rates. An additional aim was to identify and describe morphology in the vicinity of the headwaters of the tidal creeks to determine their potential association with parts of the estuarine reaches of rivers subject to different tide versus flood discharge relationships. The potential for interplay between large magnitude meteorological and oceanographic physical processes to drive changes on the floodplains is also briefly examined.

The rate, spatial extent and geomorphological character of saltwater intrusion in the Alligator Rivers Region have been determined from an interpretation of aerial photography available at the time the research was undertaken in 1998. The research documents coastal change associated with saltwater intrusion of the Alligator Rivers Region, and completes descriptions of tidal creek and mangrove growth in streams debouching into the southern waters of Van Diemen Gulf. The progress of tidal creek extension and mangrove encroachment of the Wildman, West Alligator, South Alligator and East Alligator Rivers of the Alligator Rivers Region was reconstructed from aerial photographs for the years 1950, 1975, 1984 and 1991 and mapped at a scale of 1:100 000.

Growth of tidal creek networks occurred in the eastern rivers of the Alligator Rivers Region, particularly the Wildman River and South Alligator River. Changes in the spatial characteristics and distribution of the tidal creeks and mangroves indicate that the saltwater reach has significantly expanded along extending creeks since 1950 in a manner similar to that reported from the western Gulf coast. Expansion of tidal creek networks occurred through 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 for the four river systems examined.

It is possible the semi-enclosed basin of Van Diemen Gulf, with its deep basin and broad nearshore shallows along the southern coast, amplifies the effects of northerly monsoonal winds, particularly strong northwesterlies, on water levels along the southern shore. Drier than average wet seasons with strong onshore north westerly winds would be associated with above average water levels in the southeastern Gulf and enhancement of tidal activity on the flood plain surface. If this is so, then the changes observed along the southern shore would be geographically restricted and subject to reversal with a return to more average and higher rainfall conditions. The gradual, sustained increase in northerly winds over the historical period supports this argument. Additionally, areas of saltwater intrusion at Point Farewell and Kapalga show evidence of *Melaleuca* spp regrowth. This may indicate that saltwater intrusion has occurred as part of the natural variability of the wetlands and the processes driving it are contributing to raising the elevation of the floodplains through splay deposition at the headwaters of the tidal creeks. However, these propositions cannot be tested without detailed analysis of the post 1991 satellite imagery and aerial photography now available coupled with long-term sea level observations from the Gulf, closer identification of the processes involved and examination of the patterns of vegetation regrowth at a site level.

Key words: Alligator Rivers Region, saltwater intrusion, mangrove encroachment, tidal creek, sea level

Acknowledgments

Support for the project was provided by the Department of Geography (now part of the School of Earth and Geographical Sciences) at the University of Western Australia as well as the Environmental Research Institute of the Supervising Scientist. Parks Australia North provided access to several sets of aerial photography. We are particularly grateful to Arthur Johnston, Max Finlayson and John Dodson, as well as to personnel from both institutions for their continued encouragement and support. We are very grateful to Wayne Erskine, Derek Clark and Peta Sanderson for their constructive critical comment in reviewing the document. Ann Webb assisted greatly with the production, editing and finalisation of the report.

Saltwater intrusion and mangrove encroachment of coastal wetlands in the Alligator Rivers Region, Northern Territory, Australia

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1 Introduction and background

The aim of research reported here was to determine the spatial extent and rate of saltwater intrusion in the Alligator Rivers Region which occupies the eastern half of Van Diemen Gulf in Northern Australia (Fig 1). A subsidiary aim was to link the research findings with similar, previously reported, surveys of saltwater intrusion of freshwater floodplains in the western Gulf to improve understanding of geographic variation in geomorphologic processes and saltwater intrusion. The aims required examination of the growth rates and distribution patterns of tidal creek networks associated with the estuarine rivers of the region.

As a basis for further investigation, an additional aim was to identify and describe the headwater morphology of tidal creeks. This aim was adopted to determine whether hydrodynamically dissimilar parts of riverine estuaries in the region (see Figure 14), with different tide versus flood discharge relationships, are associated with depositional fans or erosional gullies at the heads of tidal creeks (Woodroffe et al, 1987; Vertessy 1990). The potential for interplay between large magnitude meteorological and oceanographic physical processes to drive changes on the floodplains was also briefly examined.

Broad, low-lying coastal floodplains flank the southern shores of Van Diemen Gulf (Fig 1). The elevation of the floodplains is very close to mean high water spring tide level (Vertessy 1990; Wasson 1992) such that substantial inundation occurs when ocean or river water levels in the estuaries exceed the highest astronomical tide. The floodplains comprise contrasting landscapes in the western and eastern parts of the Gulf. In the west, at Chambers Bay (Fig 1) particularly, and along Finke Bay to the Wildman River, there are no rivers with well-developed tide-dominated estuarine components. Here the floodplains are dominated by extensive tracts of freshwater meadows, with billabongs and palaeochannels. Further east, the lowlands of the Alligator Rivers Region are comprised of floodplains adjoining large river systems. The largest is the South Alligator River with a catchment area of approximately 11 878 km^2 and a tidal reach extending up to 105 km inland of the coast.

During the past 50 years, freshwater meadows and billabongs of the floodplains in Van Diemen Gulf increasingly have been subject to saltwater intrusion, principally through landward extension of tidal creeks (Chappell 1988, Bayliss et al 1997). The problem 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 attributed to the impact of buffalo in tracking across low levees along tidal creeks and linking the creeks to palaeochannels. However, interactions between very large magnitude meteorological and oceanographic processes are more likely to be major drivers of floodplain development (Winn et al 2006).

The character and regional extent of saltwater intrusion around the shores of Van Diemen Gulf and elsewhere in the wet-dry tropics of Australia is largely unknown. Incursion of tidal creeks into freshwater meadows on the floodplains of Chambers Bay is apparently driven by wet and dry season differences in the relative intensities of sea-level, tide and flood conditions, with flood channels scoured in the wet season and subsequently dominated by tidal flows in the dry season. This is arguably not different from the Alligator Rivers Region although effects on superficial landforms may be very different. For example, markedly different tide versus flood discharge relationships and morphologies occur along the estuarine reaches of rivers in the Alligator Rivers Region compared with the tidal creeks of Chambers Bay (Chappell 1988). As a result the manner in which tidal networks have expanded apparently differs for disparate reaches of the river estuary.

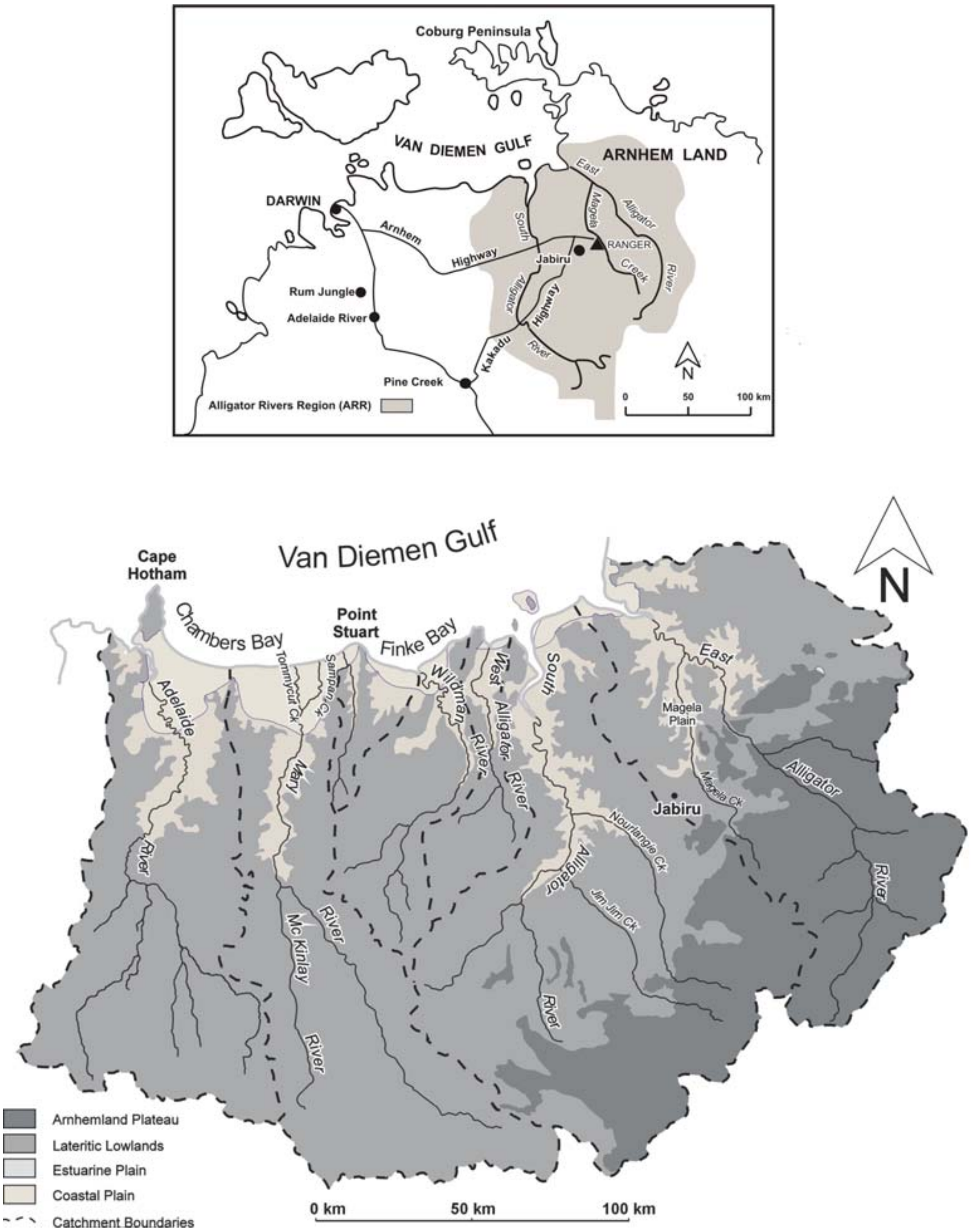

Figure 1 The biophysical regional catchments (adapted from Woodroffe & Mulrennan 1993)

1.1 Research context

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 (Fig 2). It lies to the east of Darwin (Fig 1); includes all of Kakadu National Park – a reserve of World Heritage significance; and is part of a biophysical region encompassing all coastal wetlands from Cape Hotham to the western flank of the Coburg Peninsula. Rivers with long tidal reaches include the Wildman, West Alligator (Marangarrayu), South Alligator and East Alligator Rivers. Evidence of recent tidal creek extension and problems associated with intrusion of saltwater into freshwater environments has been observed and described within the literature for a number of rivers debouching into Van Diemen Gulf, including the Mary and South Alligator Rivers.

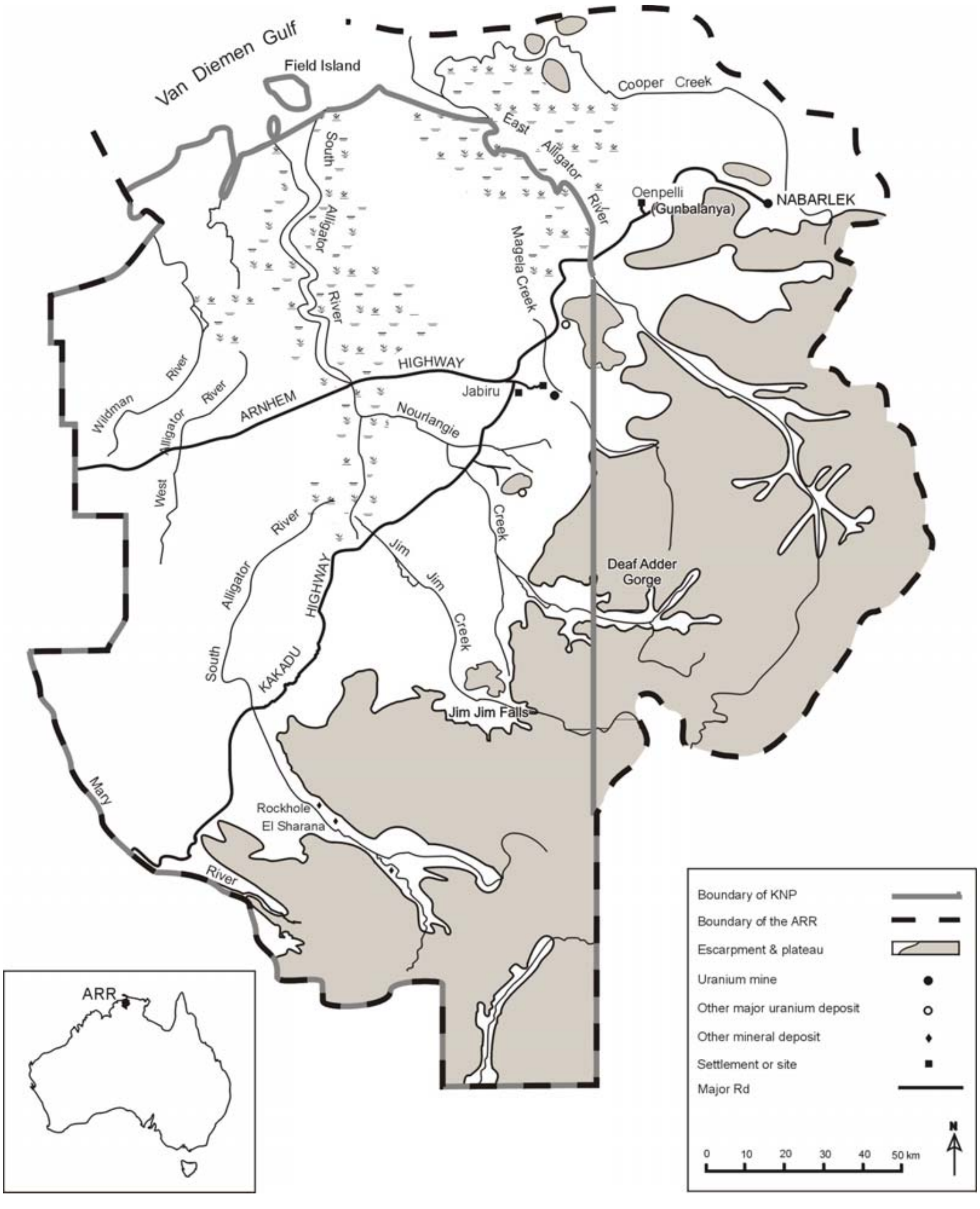

Figure 2 The Alligator Rivers Region (ARR) including Kakadu National Park

Knighton et al (1991) have documented dramatic changes to the lower Mary River floodplains associated with upstream expansion of the dendritic tidal creek network since 1950. Tidal creek expansion has resulted in the reimposition of 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 extended headward towards freshwater wetlands of the floodplains. Mangroves have encroached on creeks that have become more tidally active. Areas of upper intertidal higher level mudflats have expanded apparently due to more frequent tidal inundation. Woodroffe et al (1986) noted areas of dead *Melaleuca* spp swamp 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 that 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. Lowry & Riley (2004) subsequently found a further 21% decrease in the overall density of *Melaleuca* spp between 1976 and 1996.

2 Factors contributing to saltwater intrusion

Several very large magnitude physical factors determine biophysical changes on the floodplains and contribute substantially to the estuarine processes driving intrusion of salt water into the coastal lowlands and formation of the coastal plains. They include variability of climate, fluctuation in sea level, stream hydrology and morphology of the coastal plain. In turn, these contribute to secondary processes affecting the stability of tidal creeks, such as the distribution of vegetation communities and human use of the coastal plain. All factors require further field survey and closer examination. In particular, evaluation and modelling of the fresh and saline water interface requires a well surveyed long profile as well as surveyed channel cross-sections to identify channel width and depth in a manner similar to the surveys conducted by Vertessy (1990) in the South Alligator River for numerical modelling and a fuller appreciation of processes affecting the development of tidal creeks.

2.1 Wind and weather

Three features of the regional climate are of direct relevance to the hydrology of tidal streams: the seasonal rainfall pattern; changes in wind direction, including the frequency and the incidence of tropical cyclones and associated storm surge. Rainfall relates to run-off from the floodplains as well as water level within the main river systems. Winds, including those generated by tropical cyclones, affect waves, water levels at the coast and currents in the estuarine reaches of the rivers. Unfortunately, no wave statistics are available for the southeastern part of Van Diemen Gulf. However, the wave regime is unlikely to be a significant factor in the narrow riverine estuaries of the Gulf. In the sheltered waters of the Gulf, and especially because the shore is flanked by a broad, shallow sub-tidal terrace, the most significant processes affecting salt water intrusion of the coastal lowlands are those related to fluctuation in sea level in response to changes in the wind regime. In this respect winds are a good proxy for wave and water level change.

The climate is strongly dominated by its seasonal character, most simply classified into wet and dry seasons. As may be expected from this description, there is a sharp difference in rainfall between the wet and dry seasons. Variation in rainfall, including rainfall intensity and the duration of the wet season (Fig 3), produces an immense change in the quantity of freshwater runoff transported across the Alligator Rivers catchments. In turn, this markedly affects the salinity structure of the estuaries, pushing the salt wedge seaward during the wet season when it overwhelms the potential marine ingress produced by elevated mean ocean water levels.

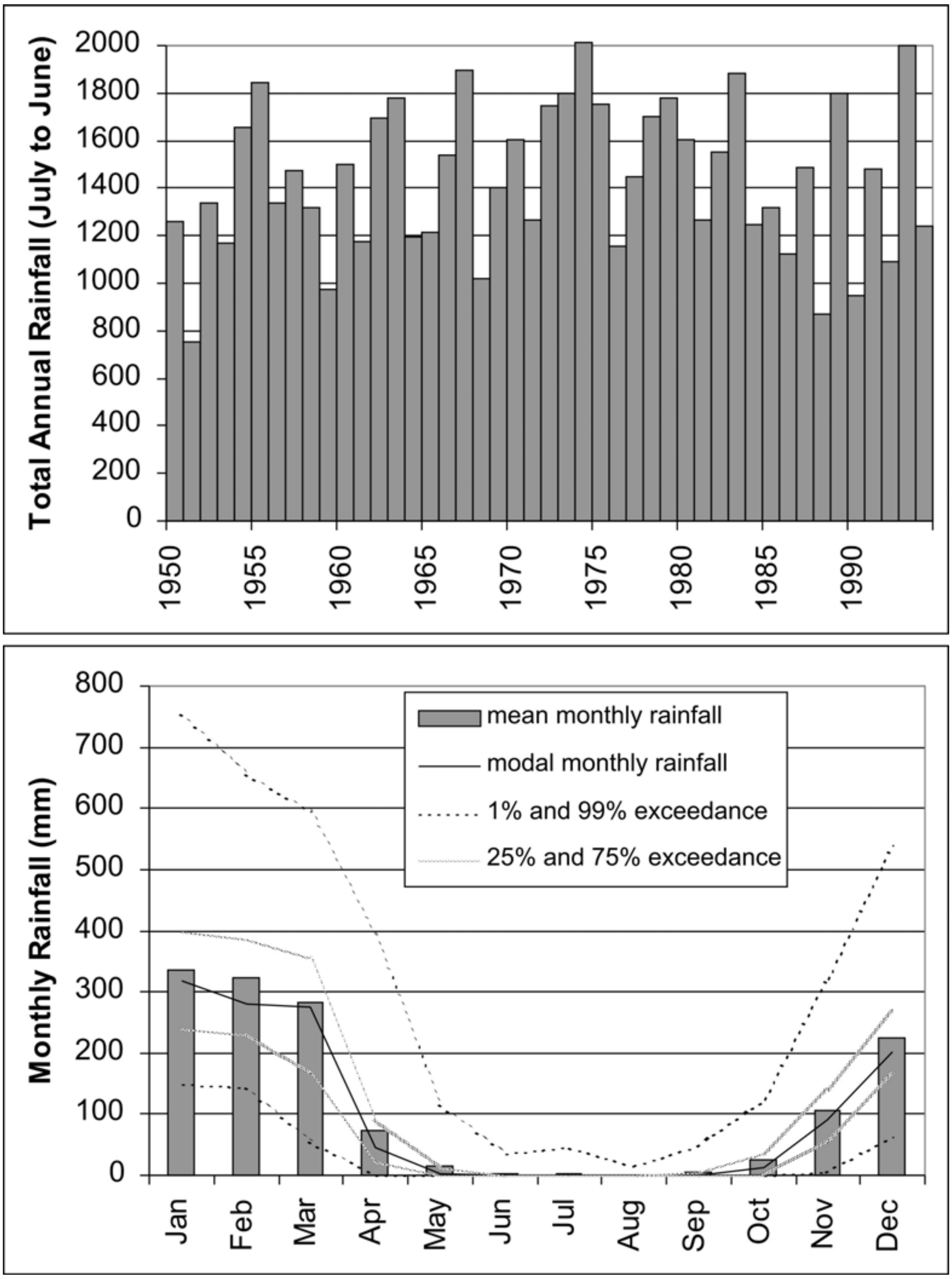

Figure 3 Rainfall at Oenpelli (Gunbalunya). Time series of total monthly rainfall (top). Monthly rainfall variability (bottom).

However, high runoff during the wet season may erode new channels or extend channels that are subsequently inundated by tidal flows during the following dry season. Further, entrenchment of channels may occur in the wet at times when river flooding is coincidental with offshore cyclonic winds and nearshore water levels are unusually low.

Wind observations at Darwin from 1950 to 1997 were used to examine the nature of the regional winds, including interannual variability of the monsoon. Prevailing weather conditions are dominated by the south-easterly trade winds during the dry season, between April and August, and the north-westerly monsoonal winds during the wet from September to March (Fig 4). The intensity of winds during 6-monthly periods incorporating the wet and dry seasons respectively is comparable with modal winds approximately 3.5 m/s and 5% exceedance winds approximately 7.5 m/s. The changing pattern of wind directions throughout the course of a year is relatively distinct, with easterly to south-easterly winds dominating in the dry and westerly to north-westerly in the wet (Winn et al 2006).

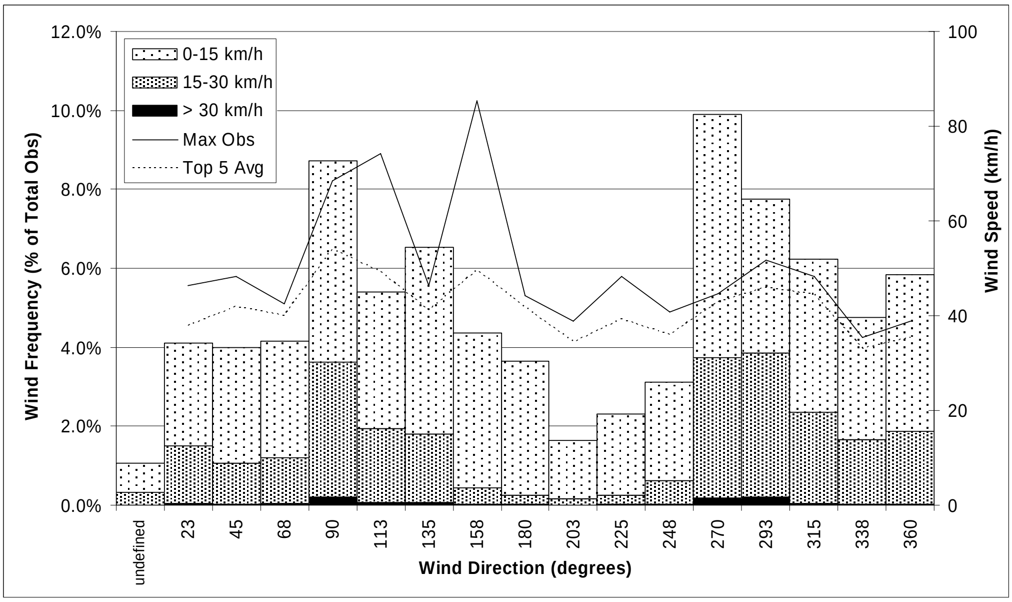

Figure 4 Wind direction, frequency and speed at Darwin from 1977 to 2004. Frequency of wind events recorded at Darwin between 1977 and 2004. The most frequent directions are those associated with the north-westerly monsoonal winds of the wet season. The variability of maximum wind speed is associated with the activity of tropical cyclones but is well below maximum gusts recorded for extreme events outside the period for which records were available for analysis. For example peak wind speeds of up to 235 km/h were recorded near Jabiru during Cyclone Monica in 2006.

The westerly to north-westerly winds produce water level set-up in the south eastern sector of Van Diemen Gulf. The set-up is expected to be highest under extreme, prolonged north-westerlies and in the vicinity of the South and East Alligator River (Green 1996). Although interpretation of the wind record is complicated by missing data, there is a gradual increase in northerly winds over the observation period (Fig 5). While more direct measurement of water levels within the Gulf is necessary to test the proposition, it is anticipated that persistent onshore winds would result in a significant increase, albeit slight, in water levels along the south eastern shore of Van Diemen Gulf over the same period. The significance derives from the close proximity of the floodplain elevation to spring high tide level.

Although strong winds may be associated with monsoonal activity in the wet (Fig 4), the extreme storms of the region are associated with highly mobile and intense tropical cyclones that occur infrequently during the wet and early in the dry. Up to 129 tropical cyclones traversed the region within a 10^o square between 1950 and 2003. A maximum of seven occurred between 1989 and 1990. Tropical cyclones may generate extreme winds from any direction depending on the cyclone path in relation to the coast and the relative intensity of the weather system.

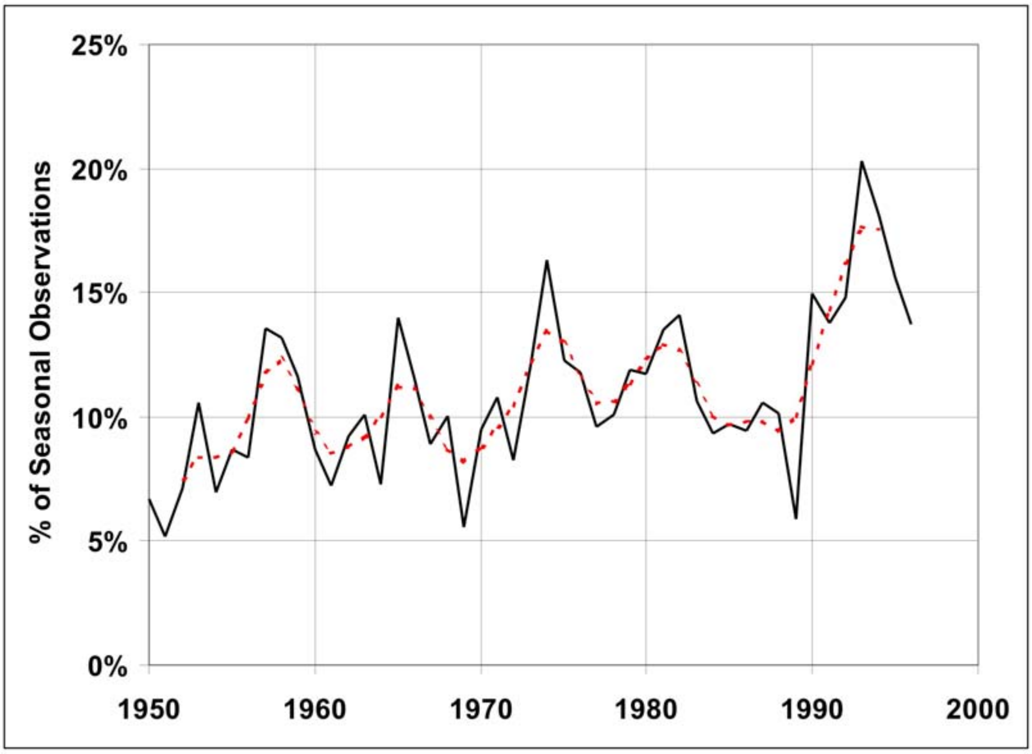

Figure 5 North-westerly wind component of the wet season. The solid line is the annual data and the dotted line the five year moving average.

2.2 Fluctuations in sea level

Unfortunately, there are no permanent water level gauges in Van Diemen Gulf. Tide gauges that are closest to the Gulf and thus the Alligator Rivers Region are the Darwin SEAFRAME gauge, a high resolution gauge serviced by the National Tidal Facility (NTF); the Darwin tide gauge which was in operation from 1/12/1958 to 31/12/1994; and the Melville Bay Gove Island tide gauge. The nearest gauging station to the Alligator Rivers Region is the Darwin SEAFRAME gauge, which began recording in May 1990. Thus water levels within Van Diemen Gulf are expected to generally follow the patterns observed at Darwin. It must be noted that these patterns become less relevant for short-period water level signals, or further upstream within the Alligator River estuaries.

Darwin is located within a macro-tidal region, experiencing semi-diurnal tides. Tidal levels nominated by the Australian National Tide Tables (Department of Defence 2002) relative to Darwin Chart Datum are shown in Table 1.

Table 1 Tide levels relative to Darwin Chart Datum

Highest Astronomical Tide	8.0 m
Mean High Water Spring	6.9 m
Mean High Water Neap	5.0 m
Mean Sea Level	4.1 m
Mean Low Water Neap	3.2 m
Mean Low Water Spring	1.4 m
Lowest Astronomical Tide	0.0 m

A seasonal tidal constituent, the sum of harmonic tidal components with periods greater than monthly, of 0.108 m has been calculated. This produces a range of approximately 0.2 m, peaking in February–March and lowest around July–August. It corresponds with the assessment of seasonal water level patterns around Australia (Pariwono et al 1986). In comparison with the tidal signals, tidal residuals are relatively small. Comparison of the monthly maximum residuals from 1995 to 2001 (from NTF) shows mild residuals of ± 0.2 m throughout the year. Whilst pressure systems contribute the majority of the residual, there is a small contribution due to mean sea level variation. More significant residuals occur during the wet season, with up to ± 0.6 m recorded over the short period of observation. The greatest residuals are most commonly related to tropical cyclone generated surge, whether by direct impact or shelf wave generation. It is considered likely that the range of residuals would increase markedly over a larger period, as the period is not representative of the entire range of tropical cyclones. In particular, passage of Tropical Cyclone (TC) Tracy in 1974 generated a tidal residual greater than 2.0 m.

Mean monthly sea level observations from 1959 to 2000 have been plotted in Figure 6. The mean annual water level varies by approximately 0.2 m, with a varying seasonal component. Linear regression of the data set suggests a trend of –0.02 mm/y for 1959 to 1997 (Mitchell et al 2001). The lowest mean level occurred in 1992 and the highest was observed in 2000.

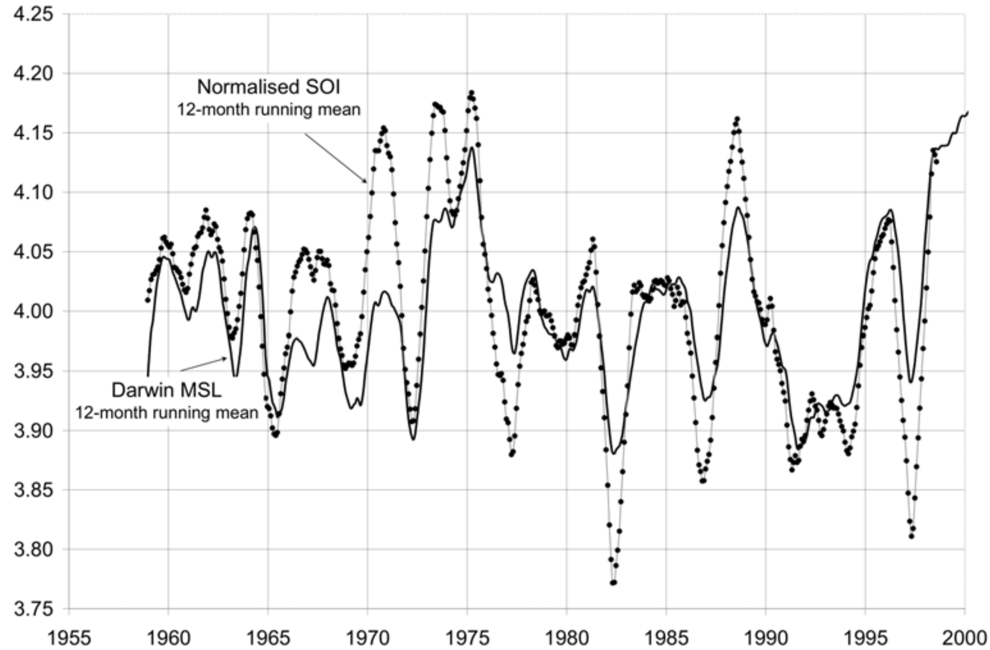

Figure 6 Sea level at Darwin and the Southern Oscillation Index

As discussed by Pariwono et al (1986), there is a strong relationship between the Southern Oscillation Index (SOI) and mean sea level. This is confirmed by the remarkable coherence between running means of Darwin monthly water level and the unscaled monthly SOI also shown in Figure 6. It should be noted that SOI holds a very strong relationship to the Darwin barometric pressure (at mean sea level), which therefore suggests a relationship between mean water levels and interannual movement of the tropical pressure belts. However, due to its latitude, Darwin is weakly influenced by the 18.6 year lunar nodical cycle. The main interannual tidal cycle is developed by the evolution of lunar perigee. This is expressed approximately as a 4.4 year cycle due to the strong semi-diurnal tidal character.

Sea level fluctuations facilitate estuary salinisation through influx of ocean water during raised water levels and efflux of estuarine water during lowered levels. This occurs over a range of time scales, including tidal cycles, storm surges, seasonal changes and longer fluctuations. The relative significance of such exchanges upon salinisation is determined by the degree to which mixing of estuarine waters occurs during each cycle and for each scale. Consequently, longer-period cycles typically have greater relative influence upon estuarine salinity.

The effect of short-period fluctuations upon salinisation is influenced by the salinity structure within the estuary and the relative degree of mixing that occurs during any water level excursion. Ryan et al (2003) suggest that for a tide-dominated estuary, high levels of mixing occur in the main tidal channel. In contrast, relatively low quantities of mixing occur in the tidal creek system. For very short-period fluctuations, such as those associated with semi-diurnal spring tidal cycles and surge events driven by the passage of tropical cyclones over several days, greater rates of mixing downstream than upstream determine that a negative surge is expected to produce a greater increase in salinity than a matching positive surge (Winn et al 2006).

Descriptions of tropical cyclone structure and character are available from a range of sources. Relatively early assessment of cyclone formation and character was provided by Gray (1975), with further detailed analysis of tropical cyclone characteristics by McBride & Keenan (1981). Cyclones' effect in generating storm surge is partly dependent on their area of generation and the path followed as they move along the coast. Tropical cyclones may generate significant positive, negligible or negative surges according to whether their path is offshore, alongshore or over land respectively. In Figure 7 this is illustrated for storm surges in the Van Diemen Gulf and water levels recorded at Darwin. Another important characteristic is the timing of tropical cyclones in short and long-term contexts. Mid-season tropical cyclones occur at the same time as the wet season, and hence any effect the surge may have on estuarine salinity may be obscured by freshwater flow.

It is important to note that the degree of upstream mixing may be dramatically increased if an excursion extends upriver beyond the tidal creek network under consideration. Analysis of extreme water level events from the 1959–1997 Darwin data set shows that a strong majority of high water level events are associated with 'king tides', the highest astronomical tides plus local set-up, rather than tropical cyclones. This demonstrates the significance of mean sea level fluctuations. Nevertheless, tropical cyclones provide potential for truly extreme water levels and must be considered. The localised nature of such impacts underscores the point that the Darwin water level history cannot be directly used as a descriptor of extreme water level events in the Alligator Rivers Region.

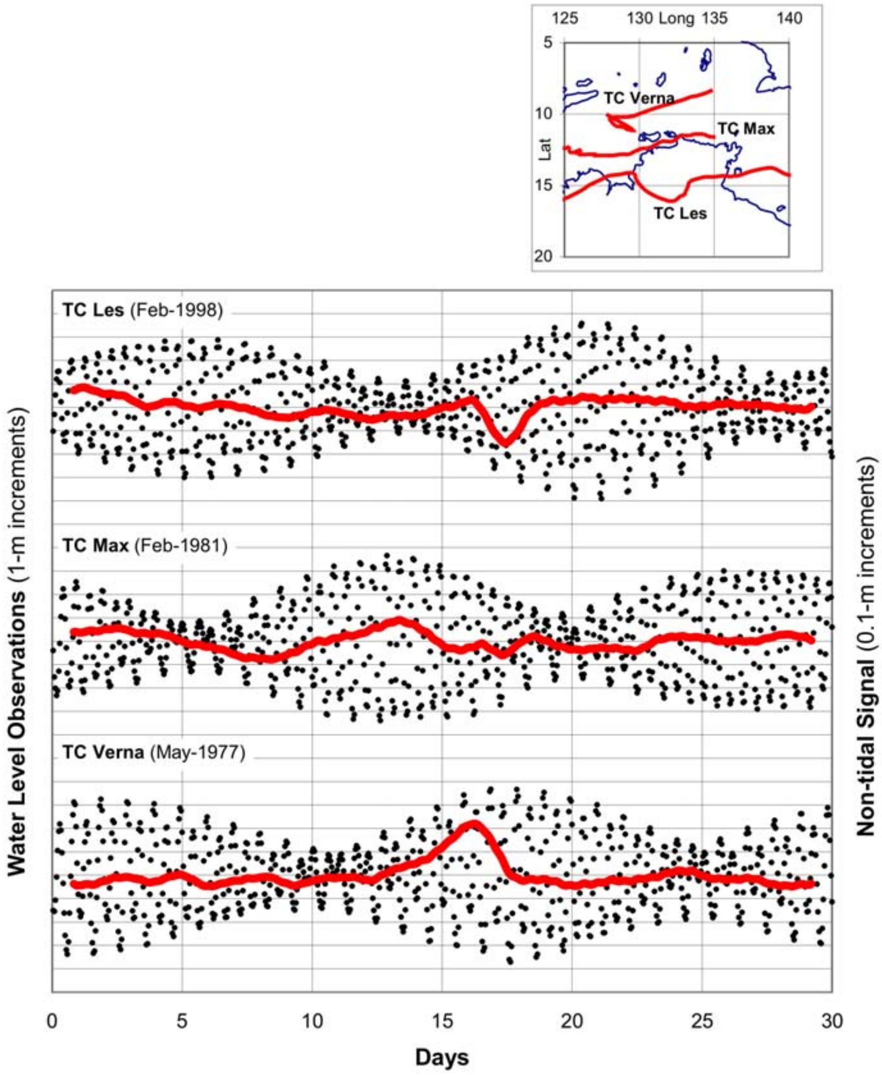

Figure 7 Surges associated with tropical cyclones. The dots indicate hourly water levels at Darwin and the solid line results from application of a two-day triangular filter. Tropical Cyclone (TC) Les displays a depressed water level; TC Max little departure from average; and TC Verna an elevated water level. The small inset shows the paths of the cyclones in relation to Van Diemen Gulf (from Winn et al 2006).

Estimation of a relative sea level fall of 0.02 mm/year has been made from a single tide gauge at Darwin over the period 1959 to 1997 (Mitchell et al 2001). Following Coleman and Wright (1978) and Kench (1999) from elsewhere, this is unlikely to be meaningful for the south eastern shores of Van Diemen Gulf due to differences in geology and the likely compaction of floodplain sediments within the Gulf. It indicates a requirement to establish differences in relative sea level change between coast abutting the horizontally bedded sandstones outcropping at the coast and the unconsolidated fluvio-estuarine silts and muds of the extensive coastal plains.

In addition, exchange may be significantly enhanced through relatively small changes of the mean sea level (Wolanski & Chappell 1995) or through change in the hydraulic character of the estuary channel (Vertessy 1990). For a typical tidal channel and basin system, a rise in mean sea level results in enhanced tidal exchange through two mechanisms. The increased depth covers a greater area, and hence provides a greater tidal prism. It also reduces the bed friction, allowing greater discharge. Whilst the latter may be significant in some cases, it is the former mechanism that holds the greatest significance, particularly for the semi-emergent wetlands or basins with shallow margins, characteristic of the Alligator River Region wetlands.

2.3 Morphology and landscape change on the coastal plains

A significant amount of scientific research has been undertaken on the Alligator Rivers Region. It commenced in the early 1970s with the Alligator Rivers Region Environmental Fact Finding Study (Christian & Aldrick 1977). Results of that research subsequently were used in an assessment of the impact of mining and milling uranium ore by the Fox Inquiry (Fox et al 1977). Research has continued in the region to gain information for the management of the National Park.

2.3.1 Morphology

A selection of landforms of the Alligator Rivers Region is illustrated in Figure 8. The geomorphology of the coastal plains of the Mary River is known from research by Woodroffe and Mulrennan (1993) and South Alligator River systems by Hope et al (1985), Woodroffe et al (1985a, b & c, 1986), the Magela Creek and coastal plains by Nanson et al (1990) and Wasson (1992), and the Point Stuart chenier sequence by Clarke et al (1979) and Lees (1987). General descriptions of landform evolution in the region have been provided by Story et al (1969), Christian and Aldrick (1977) and Duggan (1985, 1988). Detailed stratigraphic investigations of the South Alligator River system by Chappell and Grindrod (1985), Woodroffe et al (1986, 1989) provide evidence of major sea level and environmental changes in the region over the past 7000 years. These investigations provide a context for environmental changes currently occurring in the region as well as for the higher frequency changes that have occurred in the past 100 years and which may recur in the future.

Long-term changes in floodplain geomorphology, which take place over several thousand years, 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. A recent, dramatic change to the wetlands is due to incursion of tidal creeks (Fig 9) across the supratidal flats and into formerly freshwater wetlands (Fig 10). The rapidity with which the networks of tidal creeks has 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.

Maximum elevations of the coastal floodplains of the Mary River and the Alligator Rivers Region are less than five metres, and commonly close to spring high tide approximately 3 metres above mean sea level. Substantial regions of the coastal plains are at elevations below this (Wasson 1992, Woodroffe & Mulrennan 1993). Many of the remote backwater plains lie at or below the elevation reached by the highest tides (Fig 8a), yet are protected from tidal inundation by the slightly higher elevation of levee-like features that lie adjacent to the river channels (Knighton et al 1991). The low gradient of the coastal and estuarine floodplains of the northern coast, with a seaward gradient of as little as 0.5 m over 70 km, emphasises the degree to which they are vulnerable to exploitation by invading saltwater channels, or are likely to become evaporative ponds in the dry, following overbank flooding during the wet season, or during phases of extreme spring tidal fluctuation (Fig 10).

Figure 8a Floodplain of the South Alligator River, south of the Arnhem Highway, in the foreground. Freshwater wetlands, back swamp basins adjacent to higher ground, are apparent in the central background of the photograph. Photo: Ian Eliot

Figure 8b Palaeochannel on the floodplain of the East Alligator River. Photo: Ian Eliot

Figure 8c The lower right foreground shows buffalo wallows in meadows adjacent to the Mary River. Linkage of palaeochannels through incursion of tidal creeks along buffalo tracks and wallows has been suggested as one cause of salt water intrusion into freshwater meadows. Photo: Ian Eliot

Figure 8d Pig diggings and wallows on the banks of a tidal creek near the mouth of the East Alligator River. Pigs are currently responsible for disturbance of the land surface that may result in acceleration of local erosion. Photo: Mike Saynor

Figure 8 Landforms of the Alligator Rivers floodplains

Figure 9a Tidal creek crossing supra-tidal mudflats near the mouth of the East Alligator River. Mangroves line the channel and its tributaries. Shallow basins have formed on either side of the main tidal creek. Photo: Mike Saynor

Figure 9b Tidal creek crossing a mudflat near the mouth of the East Alligator River and invading a formerly freshwater wetland. Mangroves line the channel of the tidal creek. Photo: Max Finlayson

Figure 9c Tidal creek invading a formerly freshwater wetland. Mangroves line the channel of the tidal creek. The photograph shows the wetland under flood conditions. Photo: Max Finlayson

Figure 9d Dead trees in a back-swamp basin invaded by a tidal creek near the mouth of the East Alligator River. Photo: Mike Saynor

Figure 9 Tidal creeks in different landscape settings and a saline basin resulting from incursion of a tidal creek

Figure 10a First in a sequence of three photographs showing tide water incursion of a back-swamp basin at Kapalga on the South Alligator River. An incipient tidal creek is apparent as a line of dried, cracked clays in the centre of the photograph. Dead trees line the creek and salt tolerant grasses are colonising its banks. Photo: Ray Hall

Figure 10b Second in the sequence of three photographs showing tide water incursion of the back-swamp basin at Kapalga. Salt water is visible at the surface of the channel and confined by its banks. Photo: Ray Hall

Figure 10c Third and final in the sequence of photographs showing tide water incursion of the back-swamp basin at Kapalga. Salt water is no longer confined by the stream banks and is beginning to spread into the basin. Photo: Ray Hall

Figure 10d Cracked clays on the bed of the dry tidal creek at Tidal Creek near Point Farewell – East Alligator. Photo: Kristy Winn

Figure 10 Tidal incursion of a back-swamp basin at Kapalga

2.3.2 Processes

Knighton et al (1992) suggested that several factors have contributed to the vulnerability of floodplains to extension of tidal channels. They noted that tidal channels develop through a combination of extension and widening of the main channels as well as through 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). Wet season floodwaters 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).

Distinct palaeochannels are recognisable within the Alligator and Mary River regions. 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 et al 1986; Woodroffe & Mulrennan, 1993). They are apparent as billabongs, freshwater swamps and wetlands (Fig 8b), and are therefore particularly vulnerable to saltwater incursion. 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 may be preferentially invaded by the expanding network of tidal creeks. Whilst sediment size data has generally been unconvincing in demonstrating this preferential invasion by the tidal creeks, 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 erodability 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 and form saline basins.

Processes driving change on the floodplains do not appear to be thoroughly understood. Primary mechanisms of floodplain adjustment to interdecadal variation in climate and sea level, and the coupling of oceanic and atmospheric processes are not well described. In particular, oceanographic processes in Van Diemen Gulf warrant closer examination as potential drivers of coastal change in the Alligator Rivers Region. In particular, Gulf water levels and water circulation respond to marked variation in climate through phases of pronounced ENSO activity occurring at sub-decadal and longer frequencies, including a 19 year tidal syzygy. These affect sea levels and are likely to be associated with local erosion around the south eastern shores of the Gulf and in the estuaries, precipitation in the stream catchments, river discharge regimes and channel sedimentation. All require further, more detailed, investigation that is beyond the scope of this paper.

In the absence of detailed meteorologic and oceanographic information and its interpretation, the impact of large numbers of uncontrolled feral buffalo on the erosion of tidal channels has attracted significant attention within the literature as a trigger mechanism for changes in floodplain geomorphology although it may be of secondary importance only. 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) suggested a correlation between the extent of saltwater intrusion and an increase in buffalo on the floodplains, although correlation should not imply causation. Similar observations have been made on the South Alligator River floodplains (D Lindner pers comm cited in Finlayson et al 1988). However, while buffalo tracking and wallowing may have had a significant effect on the landsurface (Fig 8c), it is hard to see how it would cause widespread effects along all the channels. This is particularly apparent where creeks are lined by wide mangals or in places where the tracks cut at right angles across the long axes of palaeochannels and subsequently formed tidal creeks. The proposition that invading tidal creeks tend to run along the long axis of palaeochannels whereas buffalo swim paths and tracks cut across them is one that warrants further investigation.

Although buffalo numbers were particularly high around the period when creek networks of both the Mary and South Alligator rivers began to erode (Woodroffe & Mulrennan 1993, Bayliss & Yeomans 1989), numbers have declined in recent years due to culling to stop the spread of brucellosis. 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 and East Alligator Rivers have had varying success in preventing saltwater intrusion (D Lindner pers comm). This is an unsurprising outcome given that tributary (gully scour) and distributary (depositional fans) in the headwaters of tidal creeks indicate that some creeks are eroding salt flats and lowering the land surface whereas others are depositing sediments and raising it (Fig 11). The geography of deposition versus erosion is unknown but thought to be related to floodplain adjustment to relative change in sea level at an inter-decadal scale. Winn et al (2006) describe switching between the two states where tidal creeks have invaded a wetland basin near the East Alligator River.

Expansion of bare mudflats and the headward expansion of tidal creeks into freshwater meadows and ponds may be affected by a suite of secondary variables (Table 2). Salt water intrusion results in the death of freshwater vegetation and creation of bare surfaces susceptible to Aeolian erosion from the Gulf of Carpentaria, as has been pointed out by Rhodes (1980, 1982). During the dry season the sediment surface is smoothed by tidal flows but dries to desiccation and cracks deeply between periods of tidal inundation (Fig 10d) thus leaving the surface exposed to Aeolian processes. Dust storms were prevalent during the field investigations on the floodplains of Van Diemen Gulf and removal of fine sediment from the bare surfaces was observed during the strong south-easterly winds prevailing at the time. Sediment deflated from the surface was trapped by vegetation on the periphery of the bare mudflats and retained within the area. This is indicated by the presence of numerous micro-dunes, approximately 5 cm in height and observed close to and within patches of vegetation (Fig 12). Subsequently the microdunes may be removed by flood run-off during the wet. The significance of this secondary process in potentially lowering basin surfaces to level critical to tidal creek extension is not known although it is worthy of further investigation.

Figure 11a Floodwaters covering mudflats near the East Alligator River. Tidal creeks and their overbank distributary features are apparent in the foreground. A small tidal creek drains lowland between the levees of the two main creeks. Photo: Maria Bellio

Figure 11b Headwater tributaries of a tidal creek showing the detail of the dendritic tributaries formed by run off and gully erosion during high water conditions. Photo: Mike Saynor

Figure 11c Headwaters of a tidal creek at low tide. The main channel is approximately 10m wide. Crescentic patterns at the head mark inundations by the tide as it falls from spring to neap conditions and indicate the headwaters may be distributing water and sediment under dry season conditions. Photo: Mike Saynor

Figure 11d Small depositional fan deposited by flood tide intruding into a saline basin at Kapalga on the South Alligator River. The fan is a small version of depositional fans formed on some parts of the mudflats and coastal plains (See Figure 11a). Photo: Mike Saynor

Figure 11 Morphologic variations at the headwaters of tidal creeks

Figure 12a Mudflats on the left hand side of the photograph are an apparent source area for the rippled loess sheets on the right hand side. Photo: Kristy Winn

Figure 12b The foreground shows ripples on a sand sheet traversing salt flats at Kapalga during the Dry season. Photo: Ian Eliot

Figure 12c Loess, fine silt and clay, may be blown from mudflats and basins in the dry season. The photograph shows a layer of loess covering cracked clays on the margin of a basin near the mouth of the East Alligator River. Photo: Kristy Winn

Figure 12d Micro-dune formed in the lee of vegetation on the margin of a floodplain basin. Photo: Kristy Winn

Figure 12 Wind transport of sediment may play a minor role in deflating and lowering of dry basins during the dry season

Table 2 Relationships between the primary and secondary variables (after NCCOE 2004)

	Primary variables					
HABITATS (Secondary variables)	**Mean sea level**	**Severe weather systems**	**Trade winds & monsoonal winds**	**Rainfall & runoff**	**Wave climate**	**Isostatic change**
Seagrasses and inshore biota	Projected change in depth is small for the effect upon light penetration and water temperature.	Changes in turbidity associated with increased storminess may affect light penetration; episodic erosion of sea grass banks may occur with increased storm intensity and/or duration.	Mixing and turbidity may affect light penetration.	Localised salinity changes may occur in nearshore waters, particularly near stream mouths.	Changes in turbidity and sediment transport on the sea bed, as well as episodic erosion may occur with increased storm intensity and/or duration.	Potential change due to floodplain settlement and compaction is negligible.
Nearshore environments & sandy beaches	Adjustment of zonation in response to shoreline recession and erosion, as well as change in sea level.	Balance of erosion versus deposition alters with change in frequency, intensity and duration of onshore weather conditions.	Balance of erosion versus deposition alters with intensity and duration of onshore winds.	Changes in groundwater state of sandy beaches may contribute to rates of erosion.	Balance of erosion versus deposition alters with change in frequency, intensity and direction of onshore weather condition.	Potential change due to floodplain settlement and compaction is small.
Mangrove levees on major rivers & streams	Major changes in zonation of mangal communities; potentially large changes in salinity structure due to increased tidal exchange.	Possible defoliation due to wind stripping, sediment movement and salt encrustation. Active cheniers moved landwards.	Sediment movement due to wind effects on local wave climate.	Levee destabilisation due to flooding; basal sapping of banks on tidal creek; and movement of the saline wedge.	Affects near coastal areas; minor effects on the stability of stream banks.	Potential change due to floodplain settlement and compaction is small.
Tidal creeks & mangroves	Potentially large change in zonation; increased tidal exchange and salinisation.	Short term changes in flow patterns due to storm surges.	Secondary effects due to wind set-up of sea level.	Scouring of tidal creeks by freshwater run-off during the wet season; salinity gradient is re-established during the dry.	Not applicable.	Extension of tidal creek networks and mangrove colonisation upstream.
Mudflats and salt-tolerant wetlands	Potential increase in the area of mudflats and salt tolerant meadows	Low lying coastal mudflats inundated by major floods and storm surges.	Movement of sediment by winds during the dry season.	Extensive inundation of lowlands by river floods.	Not applicable.	Expansion of mudflats adjacent to the ocean, major rivers and tidal creeks
Freshwater basins and wetlands	Possible encroachment by mudflats and saline wetlands.	Extensive inundation of lowlands by river floods.	Movement of sediment by winds during dry season	Extensive inundation of lowlands by river floods.	Not applicable.	Invasion of palaeochannels and freshwater ponds by tidal creeks.

2.4 Stream hydrology

The Alligator Rivers Region 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 (Fig 2). 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. There is no significant groundwater mining in the region, which is largely under natural vegetation or exotic pastures. In describing the surface hydrology of the region, reference is commonly made to three of the major physiographic land surface units: the plateau and escarpment; the lowlands; and the floodplains (East 1996). Much of the information on the hydrology of the region comes from Chartres et al (1991), Kingston (1991), Nanson et al (1990) and Roberts (1991) and is summarised by McQuade et al (1996). Most recently, descriptions of the hydrology have been compiled by Walden (2000) and also by Moliere (2007) for the broader tropical rivers region.

Investigation of the hydrological record of the Alligator Rivers Region and analysis of the available information was undertaken as a first step to establishing a coastal monitoring program (Eliot et al 2000). As part of these investigations Walden (2000) noted that stream gauging stations have been deployed throughout region since 1957, and identified 39 gauging sites in rivers and along the coast of the region as being of use to the project. Despite the number of established stations, the hydrology of the Alligator Rivers Region is incompletely defined due to the highly variable and dynamic nature of its climate. 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, a lack of data describing variation in climate, and a poor knowledge of surficial sediment characteristics and distribution. Discharges at the mouths of the major rivers have not been systematically measured because tidal conditions make hydraulic rating extremely difficult (McQuade et al 1996). Additionally, extreme flood events simply overwhelm vast areas of floodplain, making it difficult to distinguish between the river mouths and the ocean (Fig 13). Despite this difficulty, estimated total annual flows at the mouths of the South Alligator and East Alligator Rivers are 2730 and 2560 million cubic metres respectively (Christian & Aldrick 1977). However, subsequent observations indicate these estimates considerably underestimate potential discharges during extreme events (Erskine & Saynor 2000).

Under all but extreme rates of discharge the river flow interacts with the tide. Chappell and Woodroffe (1985) and Chappell (1988) noted from hydrologic data of the Daly and South Alligator Rivers that the morphological differences of the channel segments appear to coincide with different tide versus flood discharge relationships. They identified four morphological components of the estuarine reaches of the two rivers (Fig 14). In downstream order these include upstream riverine, cuspate meander, sinuous meander and river mouth funnel components. The transition area of an estuarine channel where the sinuous or cuspate meanders meet the upstream segment was determined to be near the point where mean annual flood peak discharge (downstream flow) approximately equals the peak upstream flow or dry season spring tides (Chappell & Woodroffe 1985). Downstream, the transition from the funnel to the sinuous meanders of the channel occurs where the peak spring tide flow is roughly ten times the mean annual flood peak discharge (Chappell & Woodroffe 1985). The sinuous section of the river is the locus of active meander migration, where freshwater flood discharges exceed the flood tidal flows. Within the cuspate meander segment, however, the flood tidal flow is roughly equal to the seasonal freshwater flood discharge (Vertessy 1990).

Figure 13a Floodwaters covering mudflats in SE Van Diemen Gulf during an extreme flood event in 1998. The lines of vegetation across the central part of the photograph are mangroves growing along debris lines at the modal storm surge and flood inundation level. Photo: Mike Saynor

Figure 13b Floodwaters covering mudflats and mangals near Point Farewell in SE Van Diemen Gulf during an extreme flood event in 1998. The line of vegetation across the central part of the photograph is approximately at the high tide shoreline under dry conditions. Photo: Mike Saynor

Figure 13c Floodwaters covering mudflats near the mouth of the South Alligator River during a small flood event in 2002. Two debris lines are apparent in the foreground, landward of the inundated mudflat. First is a line of logs and other flotsam, while further landward is a discontinuous line of mangroves growing along a second debris line. Photo: Maria Bellio

Figure 13d The high-tide shore, mangal, saline grassland and mudflats near South Alligator River. Photo: Mike Saynor

Figure 13 Floodwaters and supratidal mudflats on the coastal plains between the East and South Alligator Rivers

Figure 14a Upstream, tidal river reach of the East Alligator River. The nomenclature broadly follows that of Woodroffe et al (1987). Riparian vegetation includes a succession of mangroves along the river bank, rainforest and freshwater meadow with distance away from the river channel. Photo: Ian Eliot

Figure 14b Cuspate meanders of the East Alligator River. The nomenclature follows that of Woodroffe et al (1987).
Photo: Ian Eliot

Figure 14c Sinuous meanders of the East Alligator River. The nomenclature follows that of Woodroofe et al (1987).
Photo: Ian Eliot

Figure 14d The estuarine funnel at the mouth of the East Alligator River. The nomenclature follows that of Woodroffe et al (1987). A tidal creek lined with mangrove vegetation crosses the floodplain in the foreground of the photograph.
Photo: Mike Saynor

Figure 14 Planform variation in channel morphology in the estuarine reaches of rivers in the Alligator Rivers Region (after Chappell & Woodroffe 1985 and Chappell 1988)

2.5 Changes in mangrove distribution

Spatial variation in the distribution of mangroves along the estuarine river systems of the Northern Territory coastline has been investigated relatively extensively within the literature, with broad-scale mapping of much of the coastline documented, and relationships between the spatial distributions and environmental factors identified (Hegerl et al 1979, Wells 1985, Davie 1985, Finlayson & Woodroffe 1996). Past research has documented supportive evidence of a close relationship between mangroves and sea-level fluctuations (Woodroffe et al 1987, Ellison & Stoddart 1991, Ellison 1993, Semeniuk 1994) and mangrove sediments have been identified as indicators of former sea level. 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 1995). This recognition has lead 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).

Stratigraphic evidence on the coastal plains of the South Alligator, Adelaide and Mary Rivers indicates that in the last few thousand years the freshwater wetlands have replaced extensive mangrove forests to form the floodplains (Clarke & Guppy 1988, Woodroffe et al 1989, Woodroffe & Mulrennan 1993). Preliminary radiocarbon and thermoluminescence data, based on the existence of shallow mangrove sediments and shoreline deposits in the stratigraphic record, indicate the coastal plains began a period of intensive progradation, with episodic chenier formation around 6000 years BP. The most rapid deposition occurred from 5000 years to 3000 years BP, with little depositional activity since 2000 BP (Woodroffe et al 1986, Clarke & Guppy 1988, Woodroffe & Mulrennan 1993). The change from a mangrove dominated saltwater regime to the extensive freshwater grasses and sedges of the coastal plains present today occurred sometime over the period of progradation. Although the plains of northern Australia have changed markedly over the last 6000 years of the Holocene (Russell Smith 1985, Clarke & Guppy 1988, Woodroffe et al 1986, Knighton et al 1991), there has been evidence of recent dramatic changes of the tidal creeks within the Alligator Rivers Region during the historical period.

More recently Landsat multi-spectral scanned (MSS) and Thematic Map (TM) imagery has been used to quantify short and long-term land cover changes on the Mary River floodplain (Ahmad & Hill 1995, Bach & Hosking 2002) to identify past and present changes in the sub-surface hydrology associated with saltwater intrusion (Jolly & Chin 1992). Additionally, Bell et al (2001) used AirSAR (Airborne Polarimetric Synthetic Aperture Radar) to map soil salinity, which is a key biophysical parameter for monitoring and managing environmental changes associated with saline intrusion. Despite extensive research conducted on floodplains of the Mary River 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. The recent changes are of immediate interest in research reported below.

3 Research objectives and methods

The objectives of the research are to:

1 map the tidal channels of the Alligator Rivers Region for each set of available aerial photography (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;

2 determine the rate and spatial extent of tidal creek expansion and mangrove encroachment within the Alligator Rivers Region;

3 where appropriate, compare changes in the Alligator Rivers with those that have occurred elsewhere around the southern shores of Van Diemen Gulf over the same time period;

4 identify meteorological and oceanographic processes likely to cause salt water incursion of the coastal plains; and

5 describe morphology in the vicinity of the headwaters of tidal creeks associated with hydrodynamically different sections in the estuarine reaches of the rivers.

The research was conducted in two phases. Firstly, aerial photographs and topographic maps were interpreted to reconstruct and map patterns of tidal creeks and the distribution of mangroves in the Alligator Rivers Region. Analysis of the aerial photography was combined with on-ground surveys to verify mapping of the most recent patterns observed on the aerial photography. The maps compiled were then used to describe topological properties of the creeks and estimate rates of changes observed for creek extension and mangrove distribution. At the time the data analysis was undertaken the 1991 aerial photography was the most recent available. Since then other remotely sensed imagery has become available including additional aerial photography in 2004. However these are not discussed in this report. The interpretations made herein, provide a base from which more recent (post 1991) changes to the tidal creeks and estuarine rivers may be assessed. Secondly, exploratory field mapping and general morphological descriptions were conducted at three sites – Point Farewell, Munmarlary and Kapalga – since these were accessible without substantial logistical support. All field work was undertaken over eight days during the month of August 1998 in the dry season. Descriptions of these steps have been outlined below.

3.1 Changes to the distribution of tidal creeks and mangroves

Tidal creek expansion and mangrove encroachment along the Wildman, West, South and East Alligator Rivers of the Alligator Rivers Region, was reconstructed from aerial photographs for the years 1950, 1975, 1984 and 1991 (Table 3). The aerial photographs were flown during the dry season of each year (May or June). This aided determination of the tidal reach of the creeks, as the creek tidal flows dominate over the freshwater floodwaters at this time. Although the photographs were seasonally consistent (Table 3), they varied in scale and quality. Mapping of tidal creeks was standardised using the method described in Knighton et al (1992) to overcome any differences. Maps of the tidal creeks and mangroves were drawn at the same working scale of 1:100 000 so that overlays could be prepared to enable comparison of topologic properties of the tidal creeks and the spatial distribution pattern of mangroves.

Table 3 Information on aerial photographs used in the interpretation

Date of Photography	Scale	Height (m)	Colour	Quality *
May 1950	1:50,000	7620	black & white	3
June 1975	1:25,000	3810	colour	1
May 1984	1:25,000	Undefined	colour	2
May 1991	1:25,000	3962	colour	1

* Quality is defined in an arbitrary ordinal scale according to the ease with which creeks could be identified, where 1 is the easiest

3.1.1 Network properties

Geometric and topologic properties of the Wildman, West, South and East Alligator Rivers, were determined as measures of the rate of mangrove growth and the modes of tidal creek extension from 1950 to 1991. Network magnitude is a topologic variable corresponding to the number of exterior links of first order channels (Shreve 1967, Schumm et al 1987), and was used as a measure of network size. The area of mangroves was calculated from the maps constructed for each year (1950, 1975, 1984 and 1991) as a measure of the rate of mangrove encroachment. The trends of network growth and mangrove expansion were depicted in graphical format for each river system and related to the spatial distribution patterns.

3.1.2 Field surveys

Three field sites, Point Farewell, Munmarlary and Kapalga (Fig 15) were selected on the basis of local knowledge of areas exhibiting evidence of saltwater intrusion and site accessibility. The latter was important given time and practical restrictions on fieldwork in the remote areas of Kakadu National Park. However, field observation of similar locations on the other river systems of the region indicate a degree of similarity that should be verified by future surveys. Tidal creeks and their immediate surrounds at each site were mapped in detail as a baseline for future measurement and assessment of geomorphic change. The three sites are described as follows:

3.1.2.1 Point Farewell

First, the site at Point Farewell is located within the estuarine funnel on the southern bank of the East Alligator River, approximately 2 km south-east of Point Farewell (Fig 15). It was selected because of the occurrence of saltwater intrusion on freshwater meadows and extensive die back of *Melaleuca* spp.

3.1.2.2 Munmarlary

Second, Munmarlary is in an area transitional between the estuarine funnel and the sinuous meanders of the South Alligator River, 30 km upstream from the river mouth (Fig 15). There is evidence of extensive growth of tidal creeks and mangrove encroachment within the confines of a palaeochannel swamp on the western flank of the river. Accessibility to the palaeochannel was impractical given logistical difficulties and time restraints on field work. Hence field mapping was conducted at the tidal creek to the east of the river. Aerial photographs taken in 1950 and 1991 indicate the creek remained morphologically stable, although mangroves have since colonised it.

3.1.2.3 Kapalga

Third, Kapalga is located on the cuspate meander segment of the South Alligator River, approximately 40 km upstream from the river mouth (Fig 15). It was selected because of its accessibility and because a single tidal creek was known to have cut into a former freshwater swamp. There was also evidence of dieback in the *Melaleuca* spp forest. The site was revisited over a number of days and the area extensively mapped.

The main morphological components of the field sites were mapped using an ASHTECH differential Global Positioning System (dGPS) to provide an accurate record of the boundaries of present site morphology. Features of each site were mapped using the Reliance rover of the dGPS with a portable Marine IV antenna. The banks of the tidal creek at the Kapalga site were mapped using the rover receiver mounted on a boat during a spring high tide of seven metres. This enabled travelling as far upstream as possible without getting stranded as the tide turned. Other features were mapped with the receiver carried in a backpack.

Features of each site that were mapped included the mangrove boundary flanking tidal creeks as an indicator of the extent of saline influence, areas of salt flats, patches of dead *Melaleuca*, boundaries of *Melaleuca* forest, tidal channels, single mangroves, areas of dead mangroves and areas of mangrove seedlings. A five second logging interval was set on the dGPS for line and area features, and a 20 second logging interval for point features. Field observations and photographs were recorded in order to document features of the site. This information included notes on the vegetation types and general distribution within the sites, soil structural characteristics and surface cover. Surface soil samples were taken from Kapalga and Point Farewell for analytical laboratory analysis (electrical conductivity from the methods of Rayment and Higginson 1992). Sites where soil samples were taken were also mapped using dGPS.

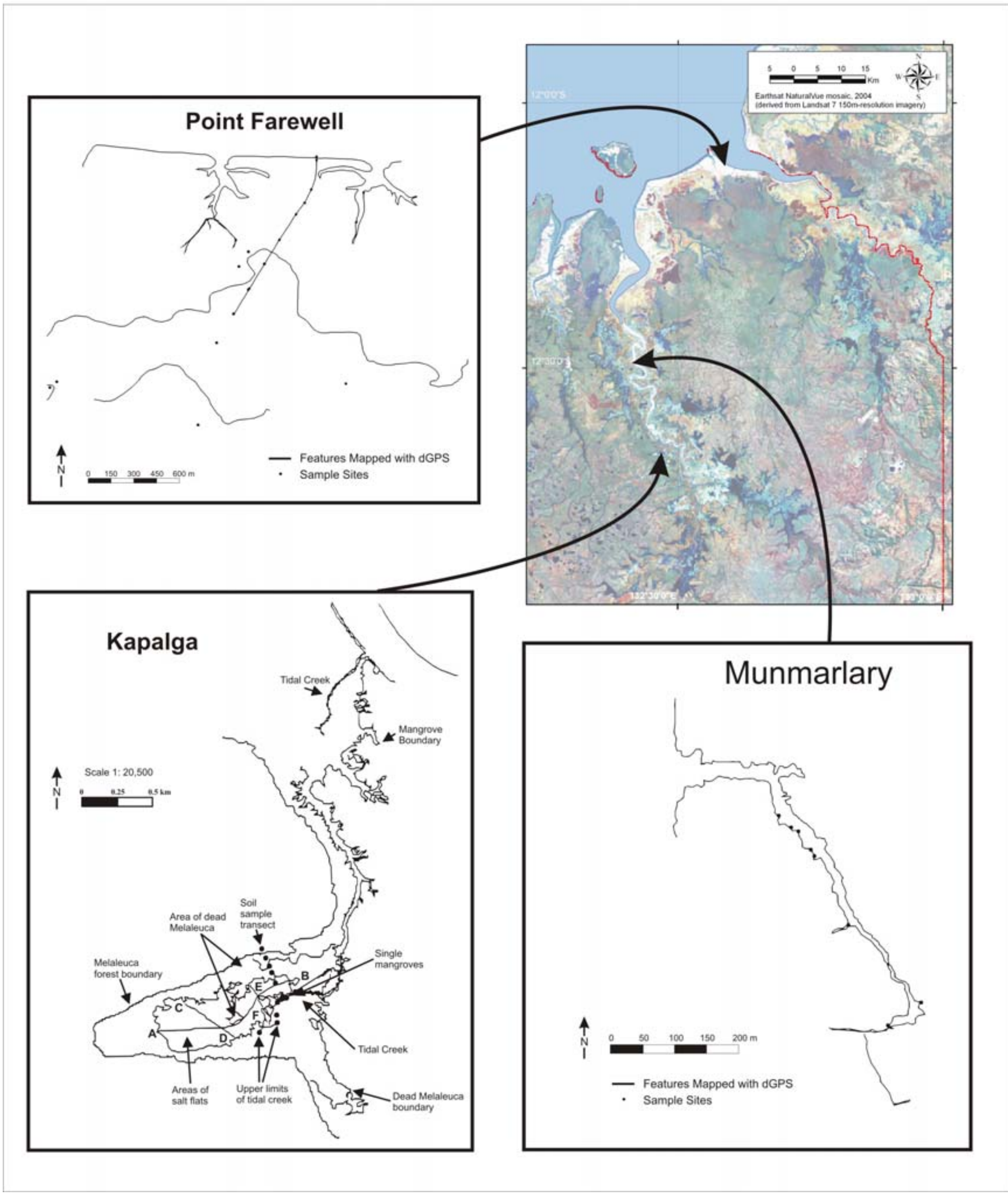

Figure 15 Location of the field study sites and dGPS maps of the morphology at Point Farewell, Kapalga and Munmarlary

The dGPS data logged in the field were down-loaded daily from both the base station and the rover receiver to the Reliance software package. The down-loaded field data were then processed using the Reliance software, which converted the corrected data to a graphical format. Logged information included recordings of latitude and longitude values, elevations, and measurements of accuracy. The processed data were exported and manipulated into Arc Info and Arc Edit to generate maps of each field site.

4 Distribution of tidal creeks and mangroves: 1950 to 1991

Since the late 1940s to early 1950s, the tidal influence of estuarine rivers in the Alligator Rivers Region has extended along creek lines and the resultant changes in the saltwater reaches have been coupled with expansion of the area colonised by mangroves. The trends of change identified from the aerial photography are separately described for each of the rivers.

4.1 Wildman and West Alligator River

The Wildman and West Alligator Rivers lie within the western flank of Kakadu National Park (Fig 2). Since 1950, tidal creeks of both rivers have exhibited marked changes in the distribution of mangroves along their banks. Mangrove encroachment has occurred along the main tributaries of the West Alligator and Wildman Rivers and along smaller creek lines as they apparently became more tidally active (Figs 16 & 17). Mangroves densely flank the shoreline of both river systems, with colonisation becoming sparser in the upper reaches of the rivers. The upstream estuarine segments of both rivers had a limited distribution of mangroves, although from 1950 to 1991 mangroves had extended approximately four kilometres upstream on the West Alligator River (Fig 17).

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 growth in the number of tributaries (Fig 18). In 1950, tributary development was relatively limited in the sinuous, cuspate and upstream sections of the river, 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 tidal creeks which appeared relatively inactive in 1950 had extended in the middle and upper reaches of the South Alligator River. A number of creeks successfully invaded the series of palaeochannels flanking the sinuous and cuspate meandering segments of the river. Small creeks also extended from the main channel in the fluvial reach.

Tributary development in the estuarine funnel was limited relative to the changes occurring on the other river segments. 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 fairly limited elsewhere. The significant contribution of small topographical features to formation of the network of tidal channels is evident from this phase of growth.

Expansion of the tidal influence along extending creek lines of the South Alligator River is indicated by spatial changes in the distribution of mangroves along the banks. In 1950, mangroves were distributed along the main tributaries of the South Alligator River (Fig 18). They had extensively colonised the shoreline and main channels of the estuarine funnel. At this time mangroves were distributed in patches along the main tributaries in the sinuous and cuspate segments, and few mangroves colonised the upstream segment of the river. By 1991, mangroves had extended to the upper reaches of the South Alligator River, which is dominated by fresh floodwaters. Mangroves had also colonised the higher order channels discharging into the sinuous and cuspate meander segments of the South Alligator River and were distributed along the creeks within the palaeochannels.

4.3 East Alligator River

The East Alligator River lies along the eastern boundary of Kakadu National Park (Fig 2). From 1950 to 1991, extension of the branching tributaries from the East Alligator River occurred in a similar manner to that described for the South Alligator River, through a combination of headward extension of the main channels and growth of the tributaries (Fig 19).

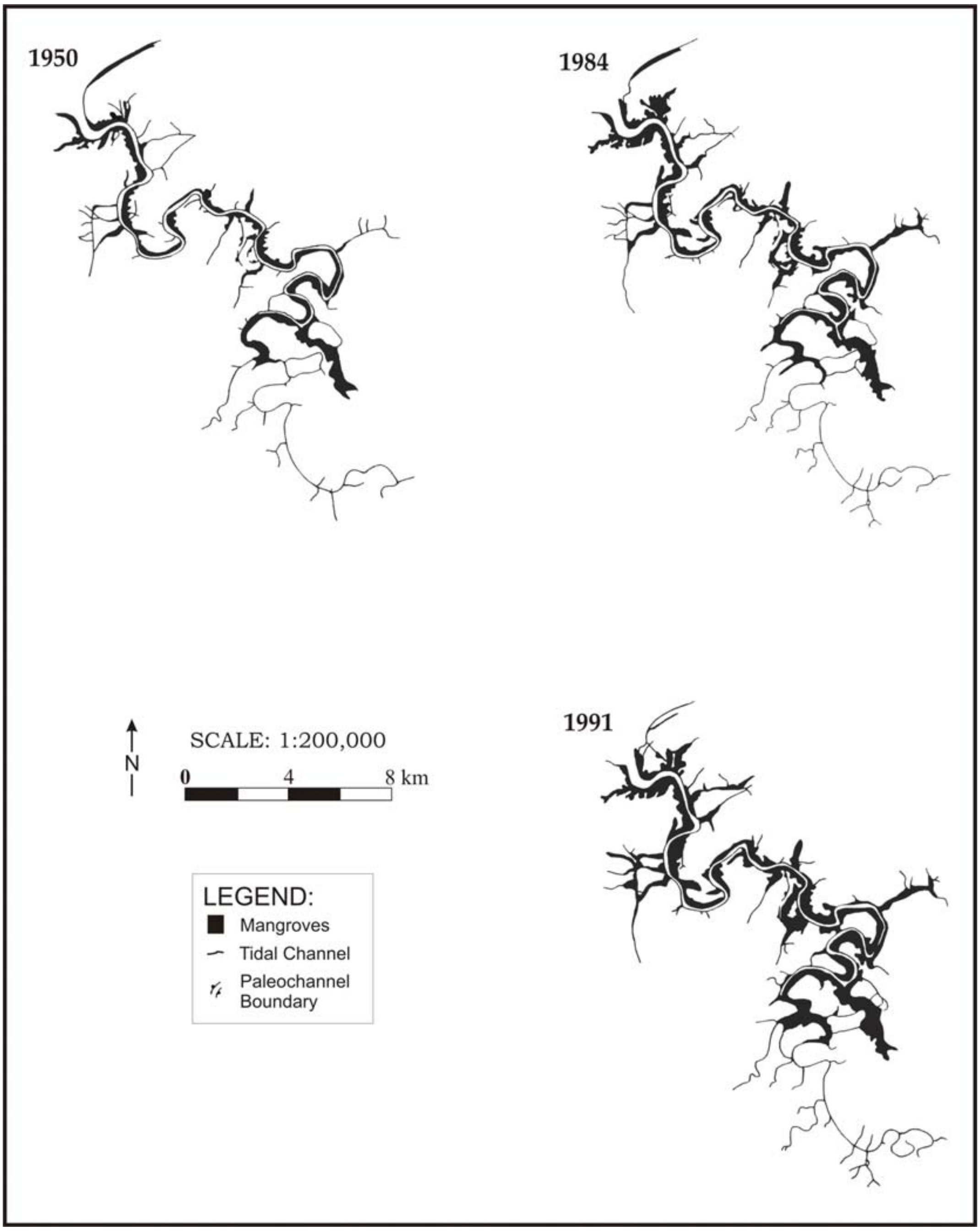

Figure 16 Tidal Creek extension and the extent of mangrove encroachment on the Wildman River, 1950–1991

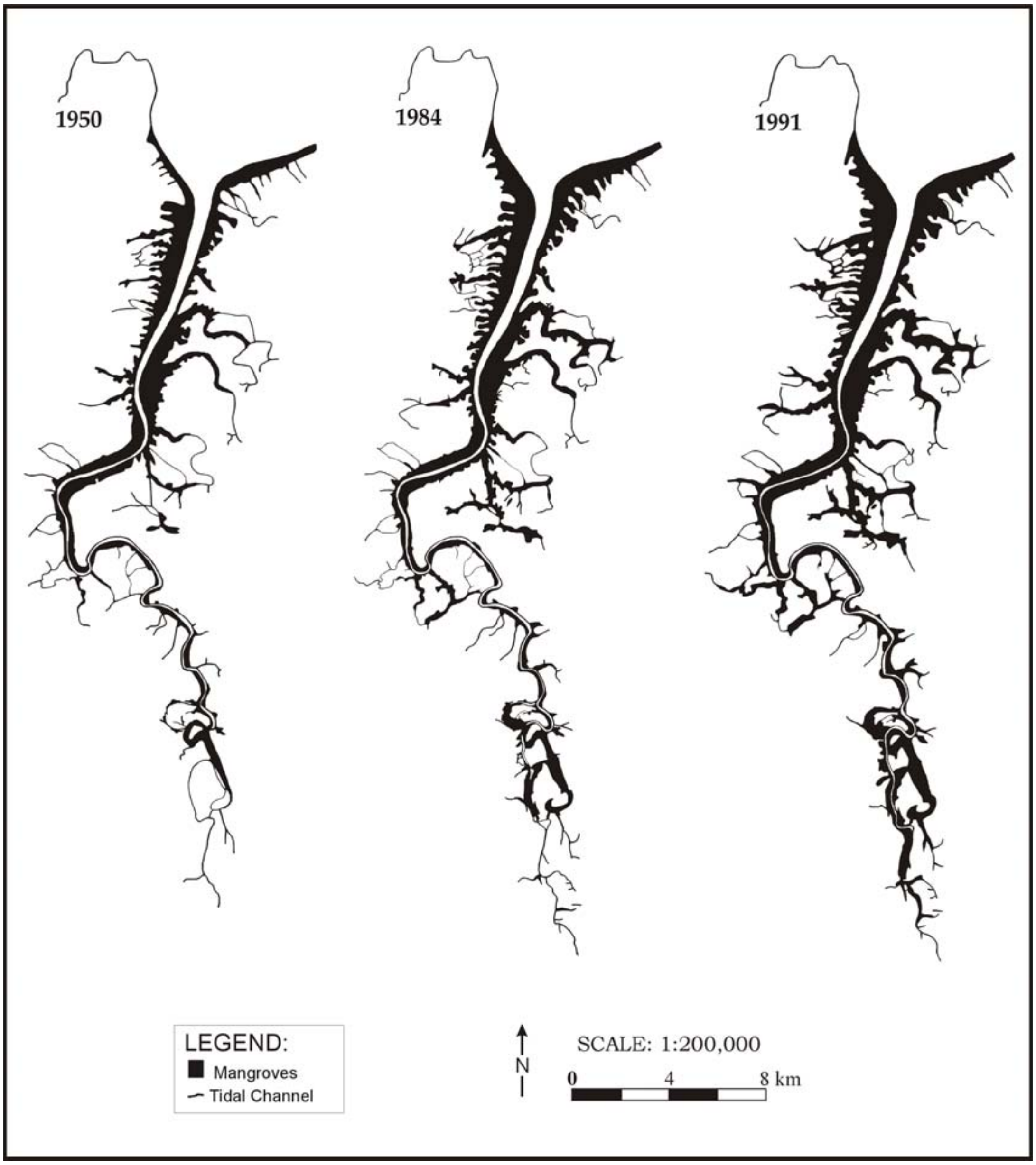

Figure 17 Tidal creek extension and the extent of mangrove encroachment on the West Alligator River, 1950–1991

In 1950, two main creeks dominated as tributaries of the sinuous and cuspate segments of the East Alligator River (Fig 19a). The creek extending from the sinuous segment had not extended further than two kilometres south of the river channel, and had few headwater tributaries. Similarly, the main tributary of the cuspate segment, 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 sinuous and cuspate meander segments of the river linked with 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 small creeks of the estuarine funnel had also extended since 1950.

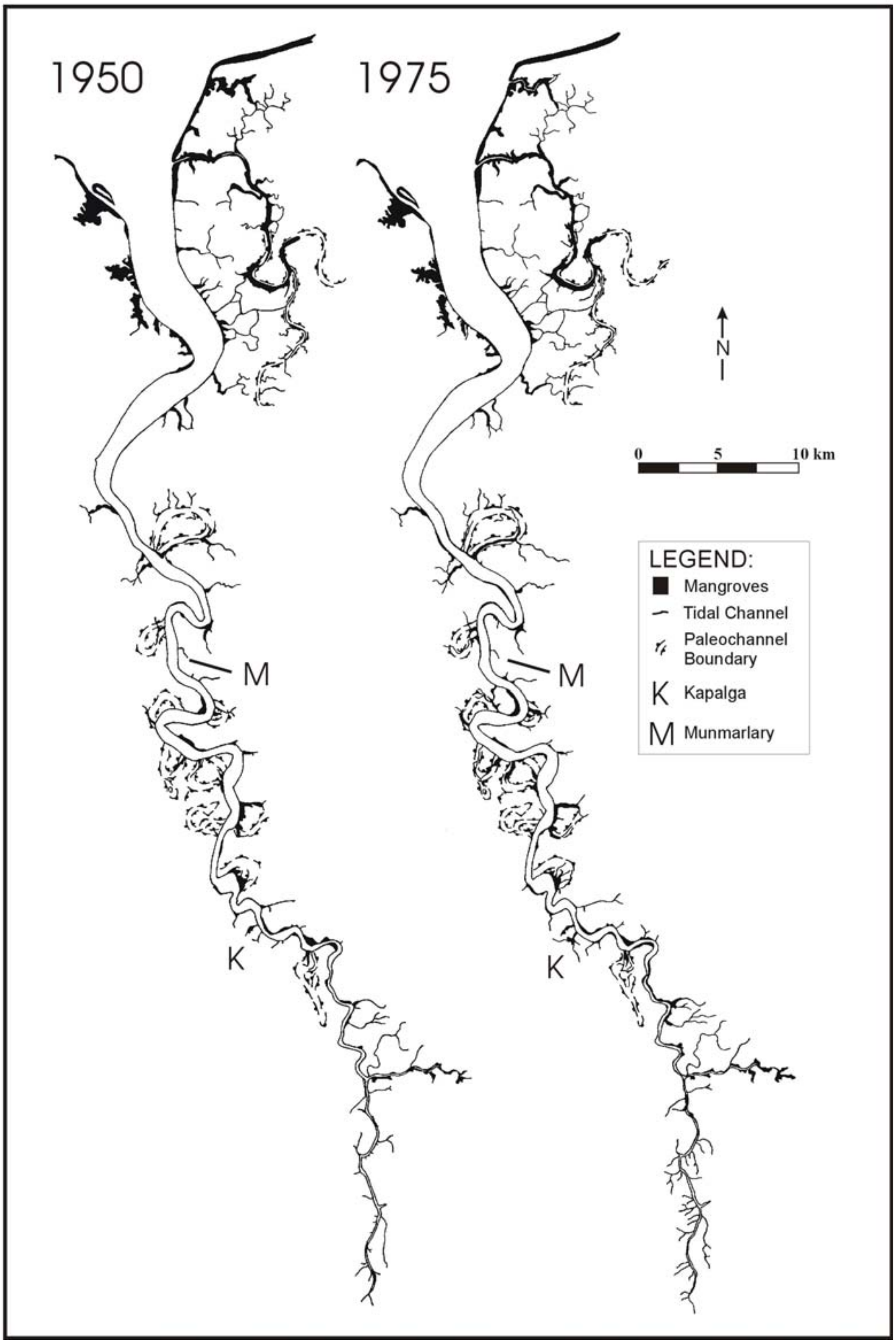

Figure 18a Tidal creek extension and the extent of mangrove encroachment on the South Alligator River, 1950–1975

Tributary growth continued in the upstream segment within the palaeo-meanders 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.

After 1950, mangrove colonisation accompanied expansion of creek lines on the East Alligator River as they became more tidally active. In 1950, mangroves flanked the shoreline of the estuary mouth, and sparsely colonised shoals and point bars in the cuspate meander segment. At this stage mangroves were generally limited to the main river channel in the cuspate meander and upstream segments of the river, although they had begun to colonise Magela Creek.Mangroves were growing on the banks of the main tidal channel on the southern flank of the sinuous segment of the river by 1984 (Fig 19b), an area which had not been encroached in 1975. This period of mangrove colonisation of the tidal channel corresponded to a lapse in the rate of tidal creek extension.

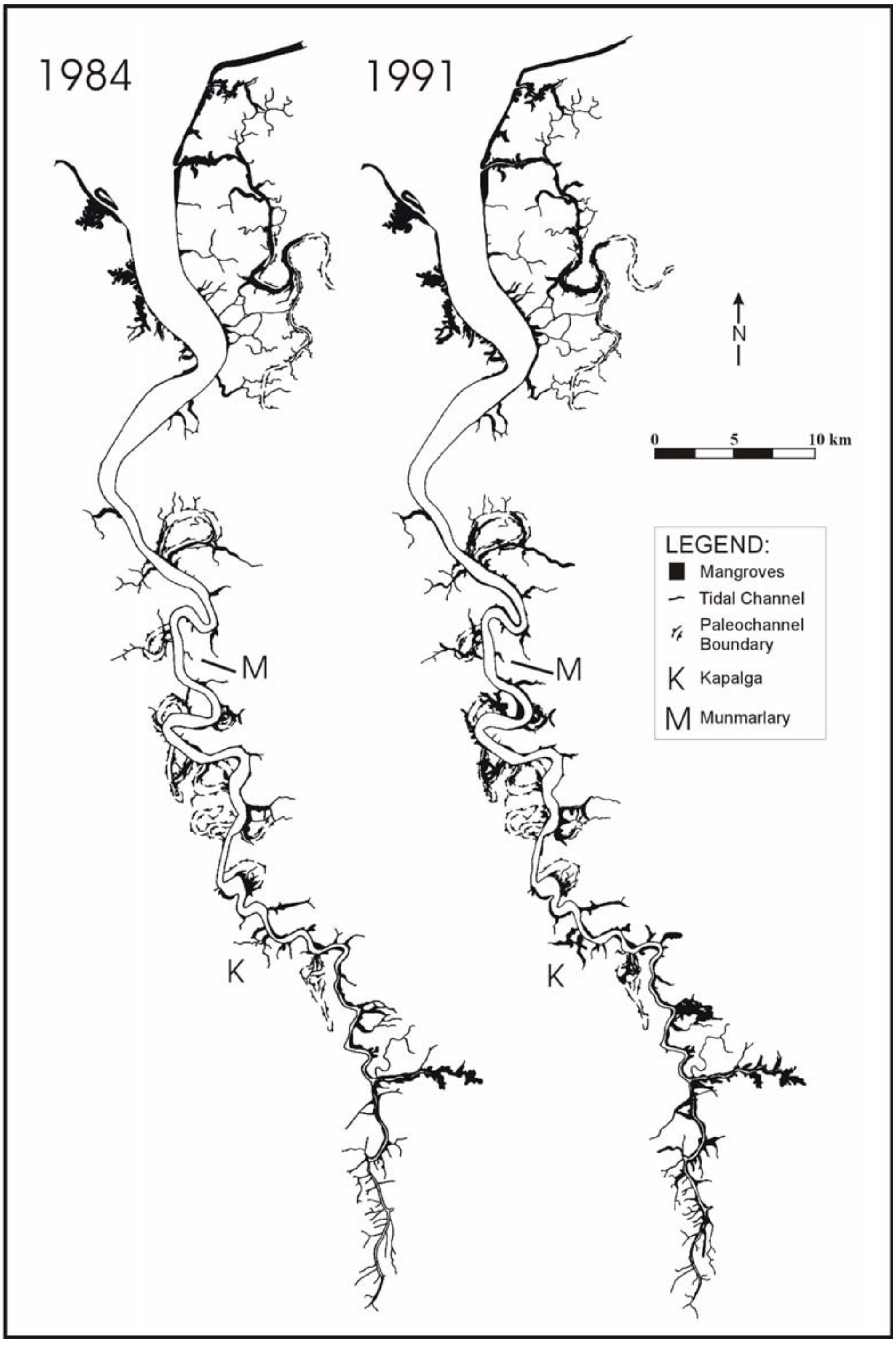

Figure 18b Tidal creek extension and the extent of mangrove encroachment on the South Alligator River, 1984–1991

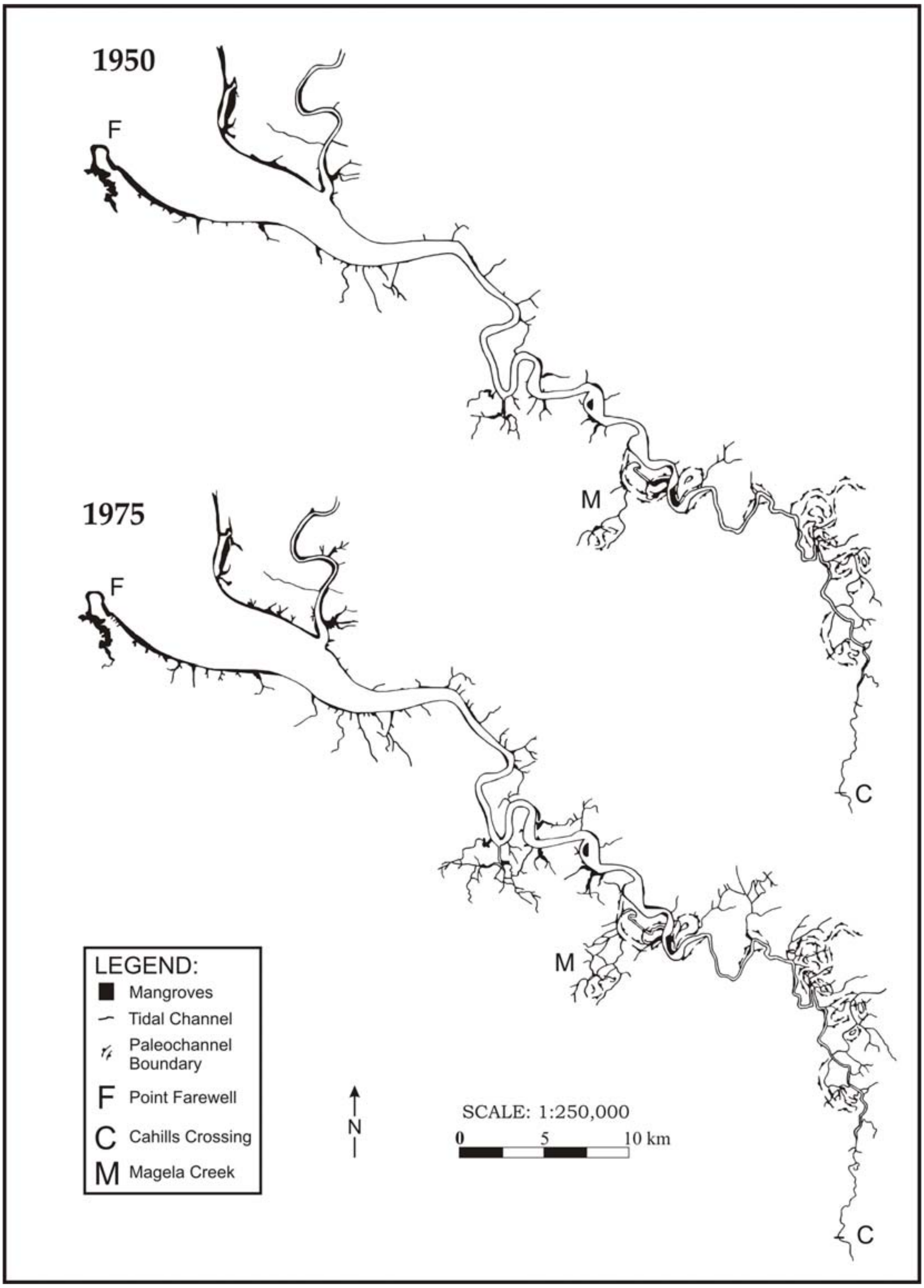

Figure 19a Tidal creek extension and the extent of mangrove encroachment on the East Alligator River, 1950–1975

By 1991, the spatial distribution of mangroves on the East Alligator River was no longer confined to the main channel. Mangroves had densely colonised the shoreline of the funnel, and had encroached some of the channels which had 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 shoals of both the sinuous and cuspate meanders were flanked with mangroves, and mangroves encroached the meander cutoff where Magela Creek joins the East Alligator River.

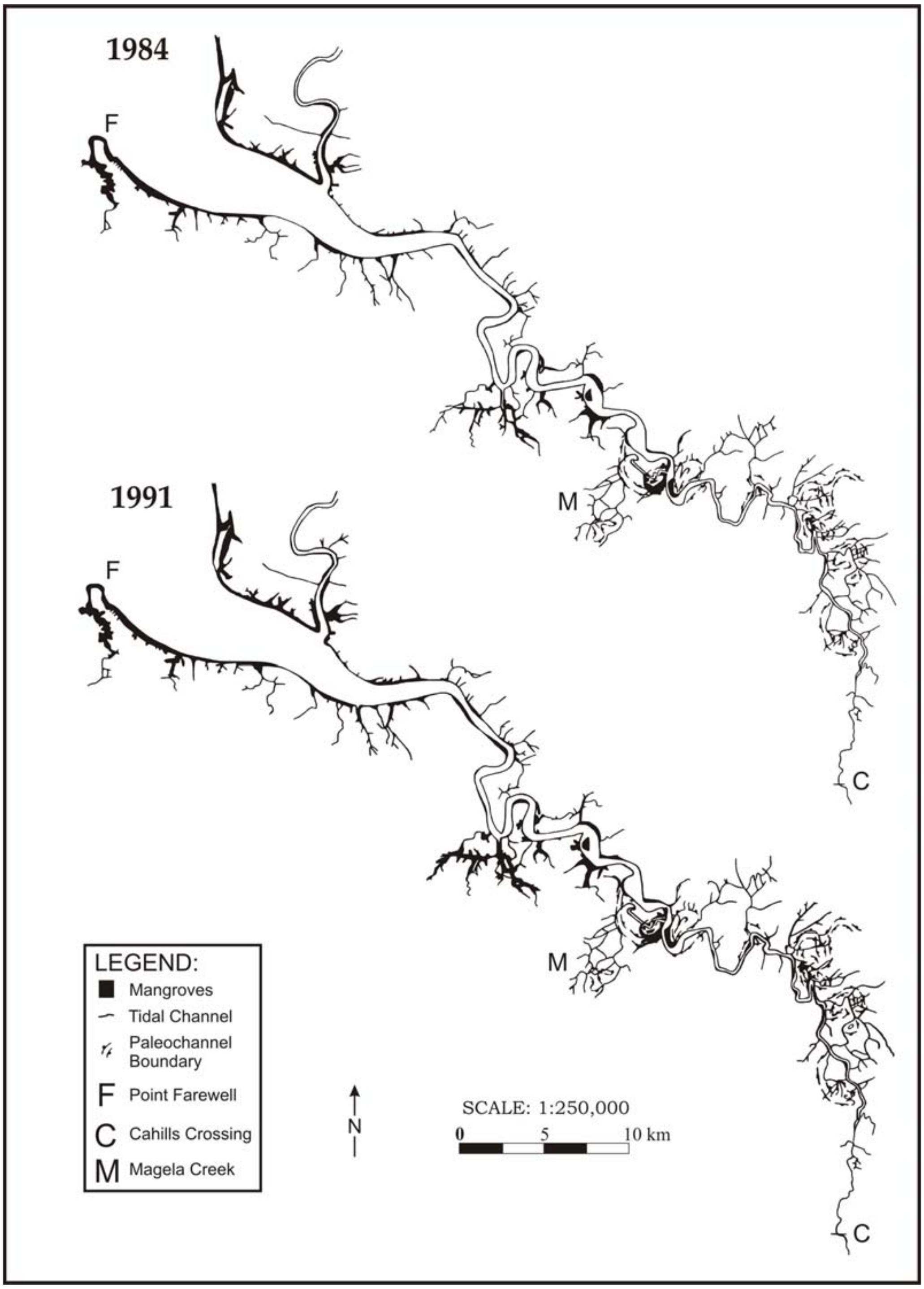

Figure 19b Tidal creek extension and the extent of mangrove encroachment on the East Alligator River, 1984–1991

4.4 Tidal creek extension

On a broad scale, Knighton et al (1992) described environmental changes resulting from saltwater intrusion of the Mary River plains similar to those in the Alligator Rivers Region. They noted that the two main creeks, Sampan and Tommycut Creeks, had experienced rapid tidal creek extension since the late 1930s to early 1940s. Using network magnitude as a measure of the network size, Knighton et al (1992) determined that both creeks experienced marked rates of growth that conform to trends observed in experimental networks.

Using network magnitude as a measure of network size, the four rivers surveyed all show a reasonably linear trend with rates remaining relatively consistent from 1950 to 1991. The South Alligator and East Alligator rivers have a steeper trend (Fig 20). There were insufficient data points describing network magnitude to establish an accurate regression (trend) line for the rivers. However, it is suggested from Figure 21 that the rates of growth changed over time. From 1984 to 1991, the South Alligator River expanded more rapidly than the Wildman, 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 estuary systems and main tributaries.

4.5 Spread in the distribution of mangroves

The Wildman, West, South and East Alligator rivers all display a rapid rate of mangrove growth from 1950 to 1991, although the rates of change between the rivers were quite varied (Fig 21). Reasons for this are not immediately apparent and are beyond the scope of this investigation due to a lack of detailed hydrological and oceanographic data for the region. Mangrove expansion occurred most rapidly on the West and South Alligator rivers, with the highest growth rates occurring after 1975. From 1984 to 1991, the total area of mangrove vegetation on the South 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 the increasingly high rate of mangrove growth on the four river systems, the trends of mangrove growth varied with the morphological changes in the river channels. Mangrove growth occurred in the upper reaches of the river, and in the estuarine funnel of the South Alligator River. Little growth occurred from the meander segments 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 those observed on the South Alligator River.

5 The headwaters of tidal creeks

The field mapping of morphology and mangrove distribution at Point Farewell, Munmarlary and Kapalga provide an indication of environmental changes taking place at the headwaters of tidal creeks in different segments of the estuarine channel (Fig 14). Used in combination with interpretations of the aerial photography it provides an indication of the extent and character of environmental change on the coastal floodplains.

5.1 Point Farewell

At Point Farewell the present distribution of the main morphological features supports the broader observations of change in the saltwater reach at the East Alligator River estuarine funnel. In 1950, the two creek tributaries mapped had each extended from the shoreline as single expanding channels, with no branching tributaries (Fig 22). These creeks since experienced rapid rates of extension and bifurcated into small creek networks. The creeks and their tributaries have been colonised by mangroves. From 1950 to 1991 the two main tributaries of Point Farewell (Fig 22) have caused extensive areas of *Melaleuca* spp to die. This occurred as saline tidal water invaded the *Melaleuca* spp forest boundary. Since 1991 there has been some regrowth of Melaleuca spp (Winn et al 2006).

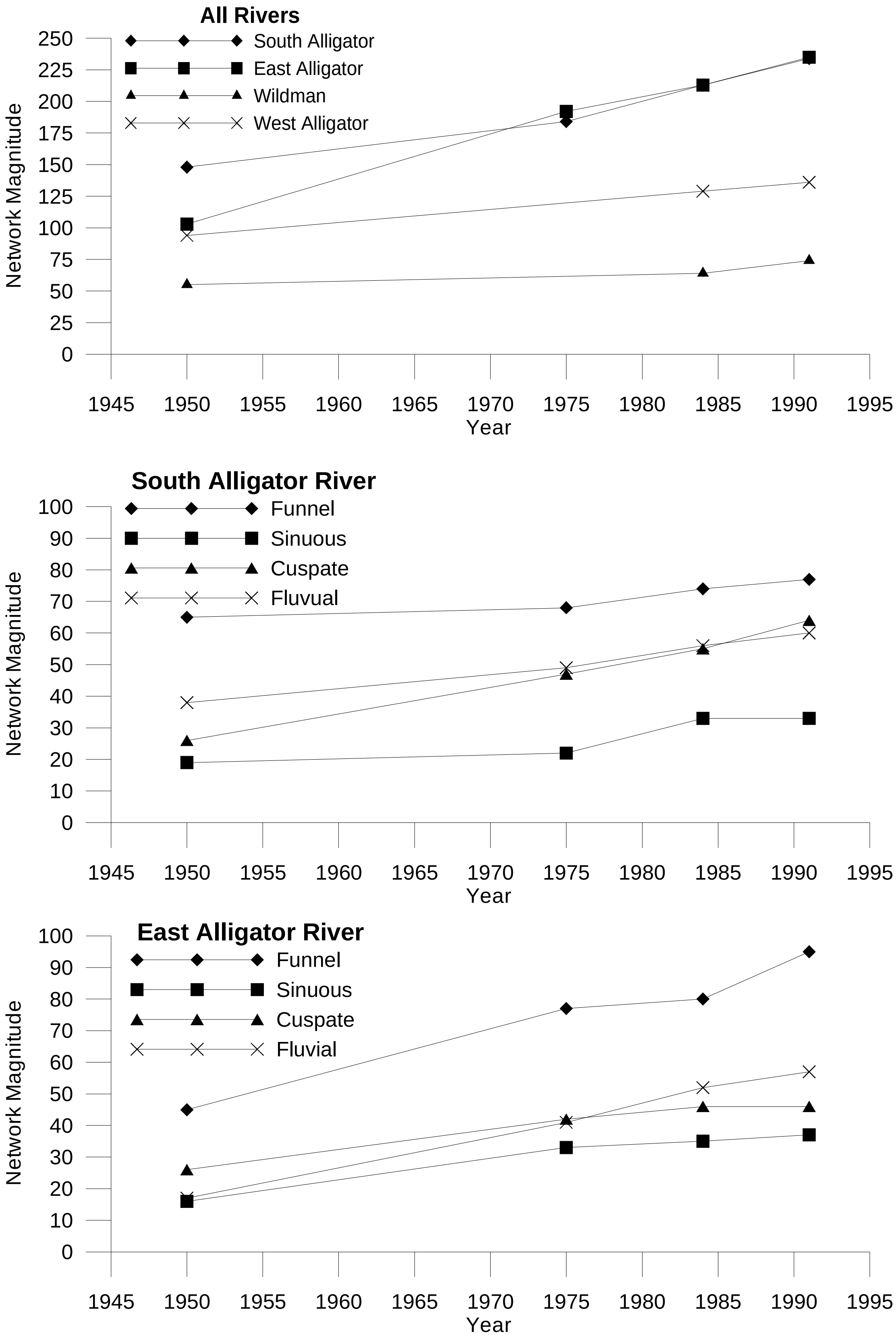

Figure 20 Changes in the network magnitude in the Alligator Rivers region, 1950 to 1991

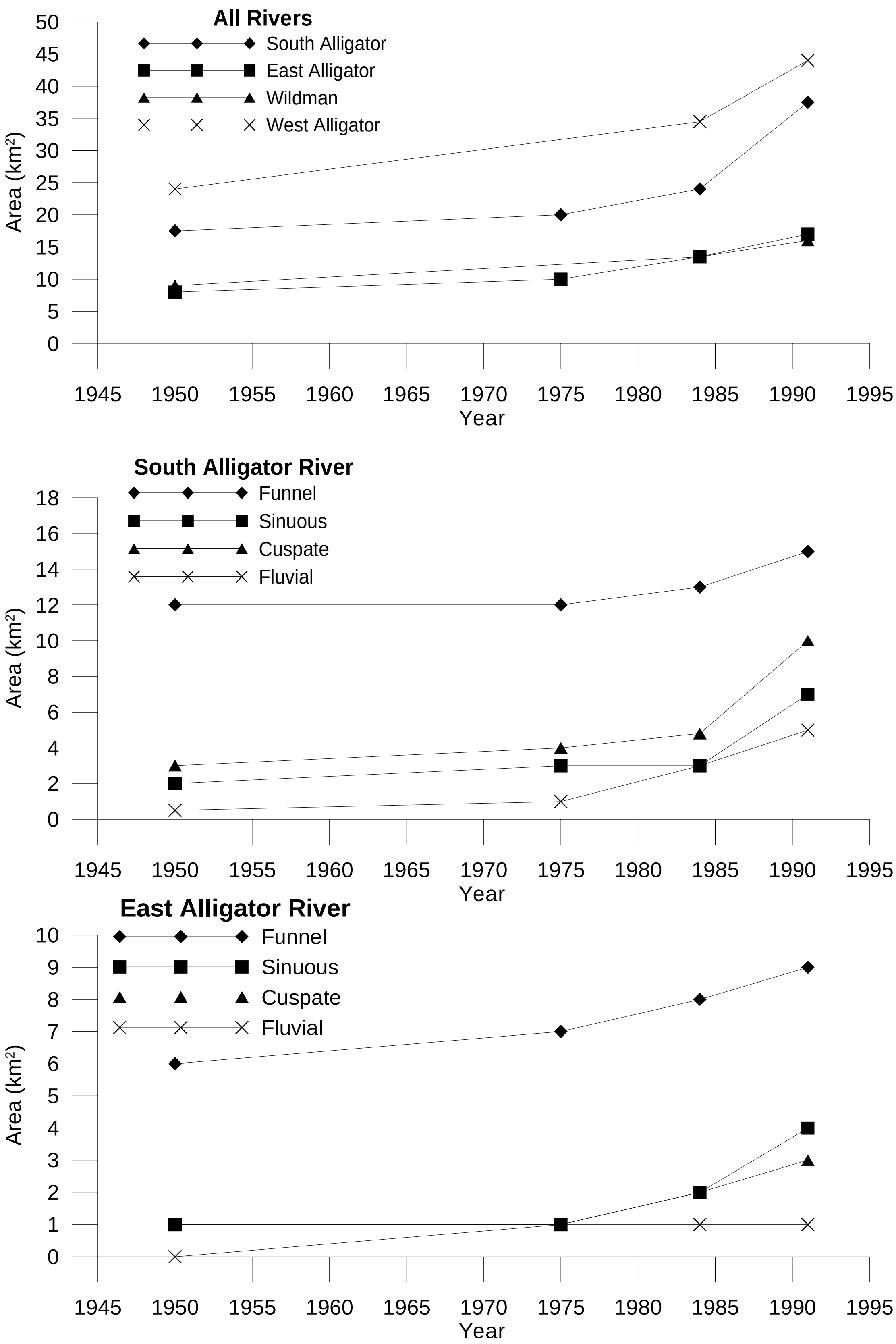

Figure 21 Spread in distribution of mangroves, 1950 to 1991

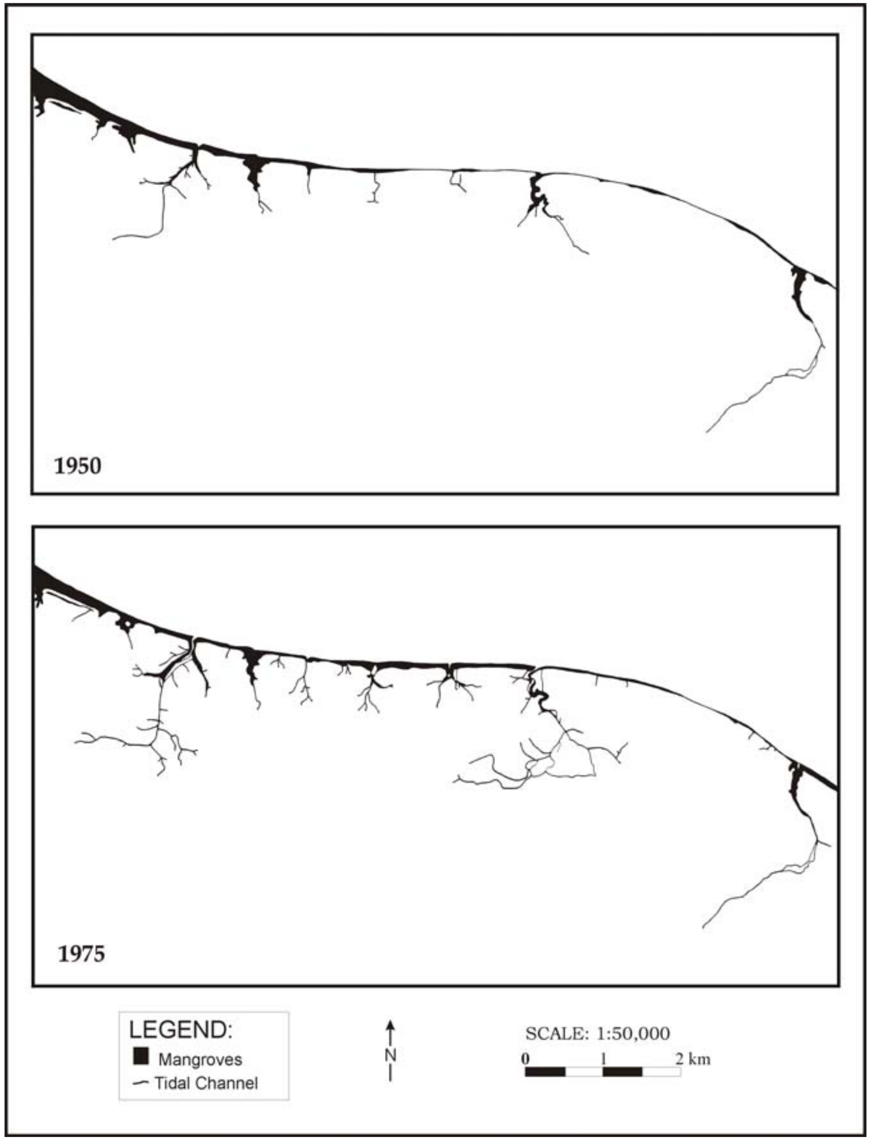

Figure 22a Tidal creek extension and the extent of mangrove encroachment at Point Farewell on East Alligator River, 1950–1975

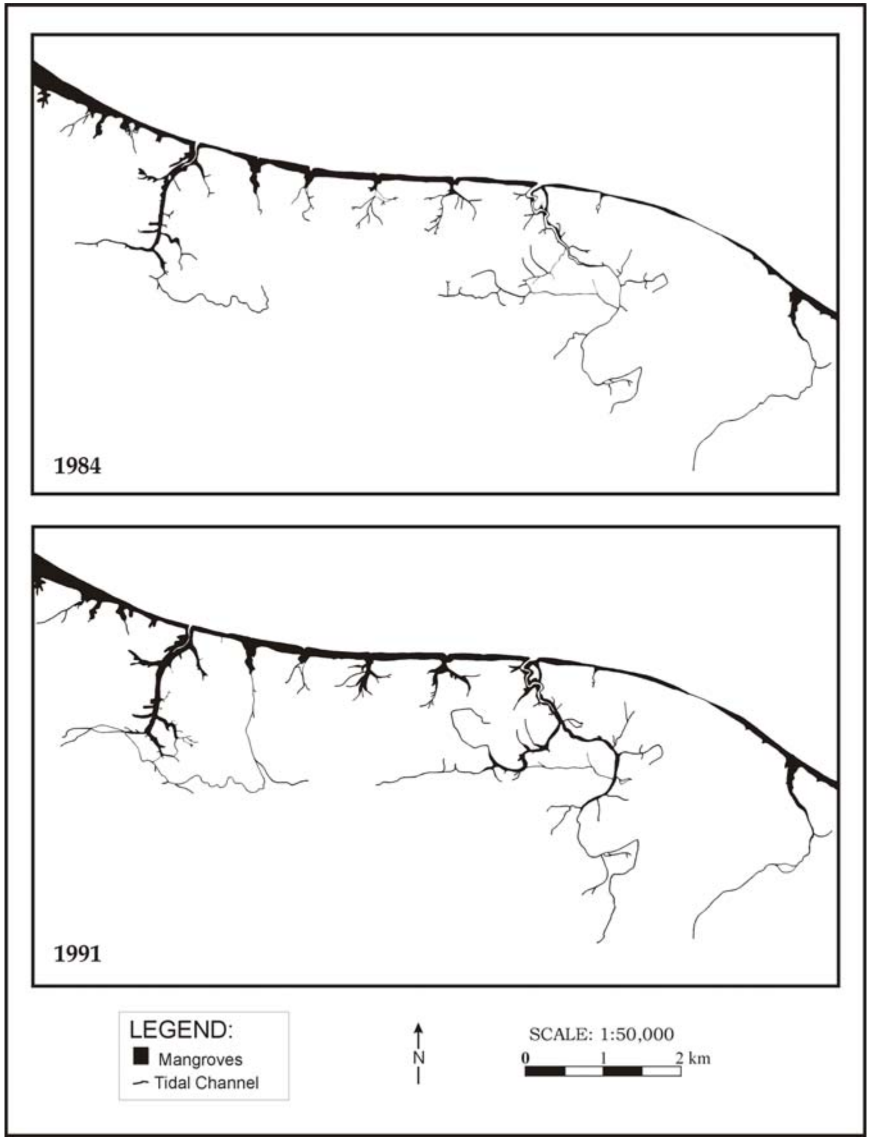

Figure 22b Tidal creek extension and the extent of mangrove encroachment at Point Farewell on East Alligator River, 1984–1991

The tidal creeks at Point Farewell have incised channels through low-lying coastal salt flat which extends over 500 metres inland in some places. Aerial photographs of the region in 1950 and 1991 indicate that the area of coastal salt flat has increased since 1950 at the expense of low-lying grassland. A distinct boundary exists between the grassland and the salt flat on the coastal plain, suggesting that the grasses are retreating in response to an increase in the saline reach. There is a marked difference of soil salinity between the salt flat (Table 4, site 3) and grassland (Table 4, site 4).

Table 4 Soil electrical conductivity of samples at Point Farewell

Sample Site	Site Description	Soil EC (mS/cm)
1	Creek channel	7.98
2	Creek headwater	18.89
3	Salt flats	41.30
4	Grassed area	6.10
5	*Melaleuca spp* dieback	6.19
6	*Melaleuca spp* forest	1.19

5.2 Munmarlary

From 1950 to 1991, extensive growth of tidal creeks and mangrove encroachment occurred within the confines of a palaeochannel swamp on the western flank of the South Alligator River, near Munmarlary (Fig 23). In 1950, the tidal creek consisted only of two tributaries that extended along the edge of a palaeochannel. Mangroves had also colonised the downstream limit of the creek. By 1975, the southern tributary had significantly extended, and had made a second link to the river channel. Mangrove encroachment had been limited. The mode of growth was primarily headward extension, with the initiation of few small tributaries. By 1984, the southern creek tributary had rapidly grown, through both headward extension and the growth of a number of first order tributaries. Further tidal creek extension appears to have been limited in the palaeochannel, and extensive mangrove colonisation had occurred throughout the vicinity of the recently expanded creeks by 1991.

In contrast to the west bank, little growth of tidal creeks occurred on the eastern flank of the South Alligator River at Munmarlary over the same period. A single creek adjacent to the palaeochannel in 1950 had shown little significant growth or signs of saltwater intrusion until 1991, when mangroves had colonised the main length of the creek (Fig 23). The upper limits of the tidal creek currently remain largely unaffected by mangroves, although patches of dead mangroves flank the upstream reaches.

The deaths of mangroves, notably *Avicennia marina,* suggest that the creek has experienced a phase of channel abstraction in the upper reaches. Mangrove encroachment tends to occur in response to channel expansion of the tidal influence along creek lines. However, the spread of vegetation helps to trap fine sediment suspended in the creek. The upper reaches of the smallest tributaries are most affected and may be choked or totally infilled by increased sediment deposition. Mangrove dieback may be indicative of the subsequent restriction on the saltwater reach. In contrast to this trend, there was evidence of new mangrove growth on the western edge of the creek downstream, indicative of the extent of the saltwater reach along the tributary.

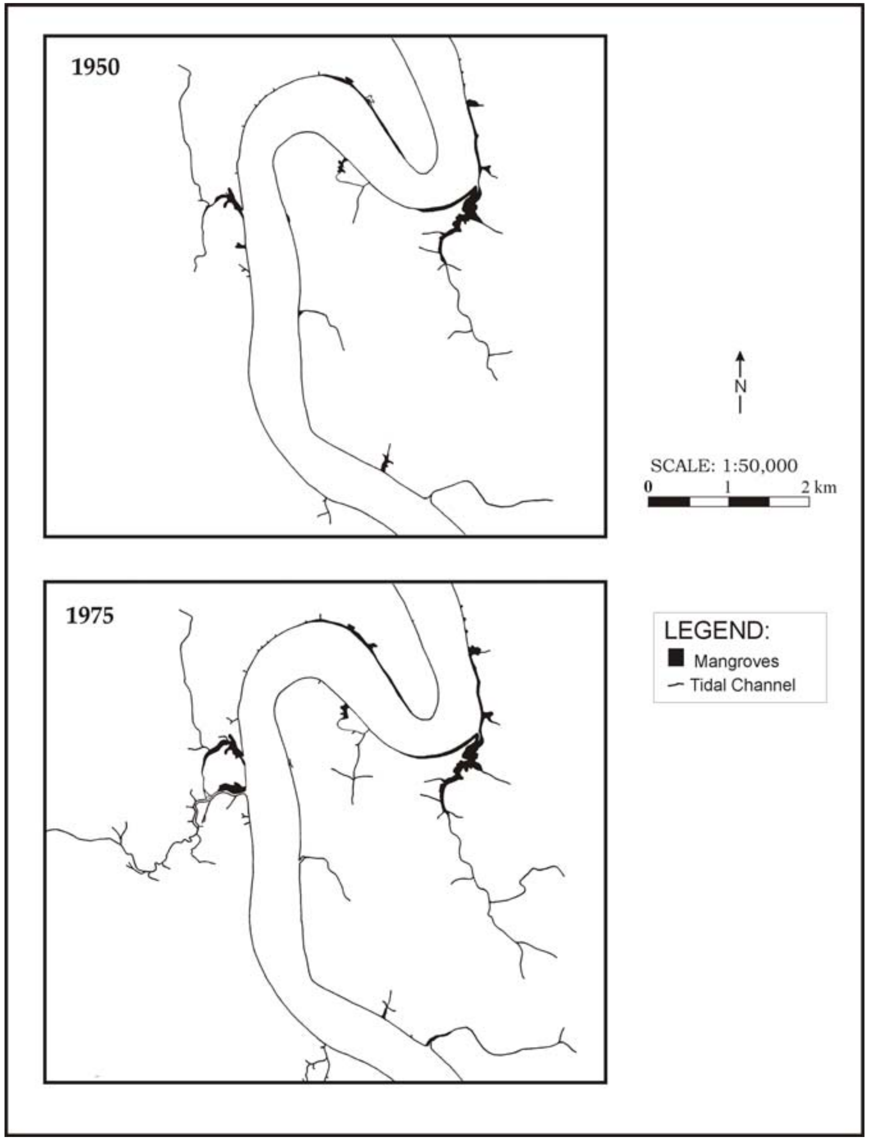

Figure 23a Tidal creek extension and the extent of mangrove encroachment at Munmarlary on the South Alligator River, 1950–1975

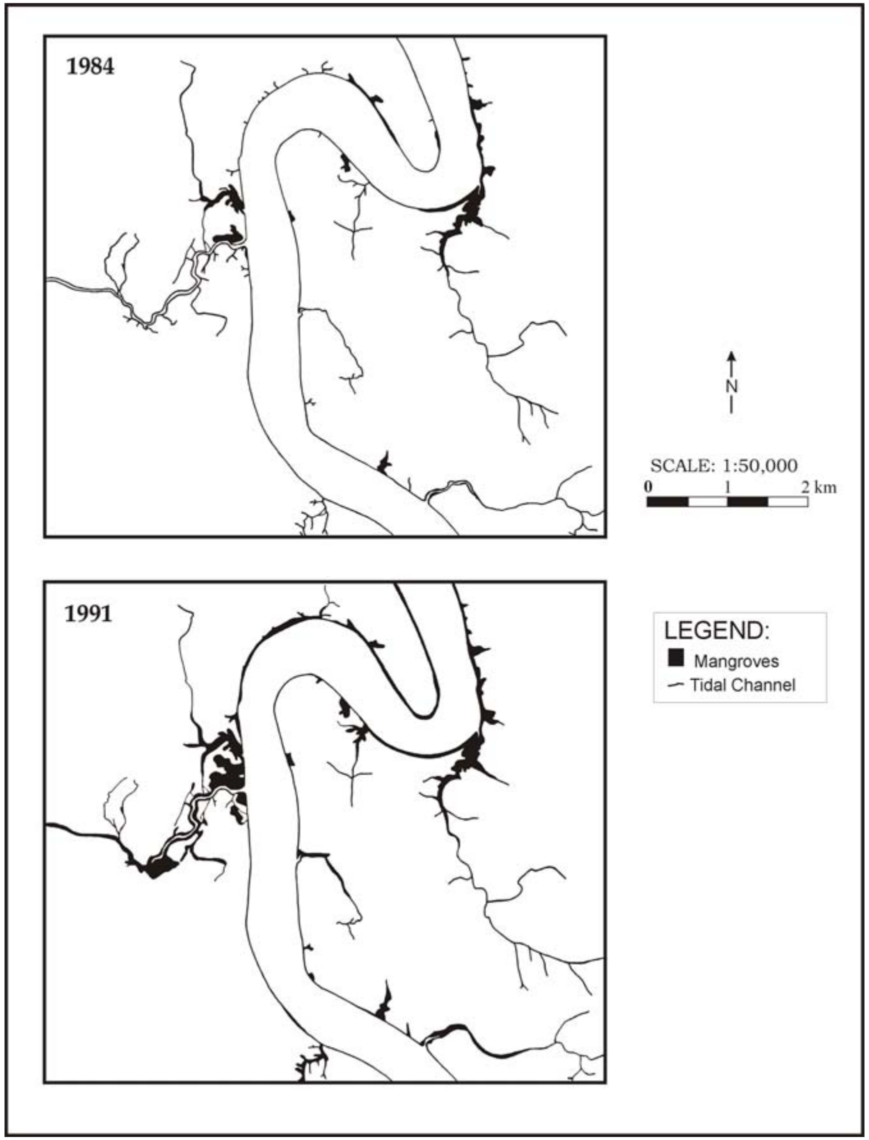

Figure 23b Tidal creek extension and the extent of mangrove encroachment at Munmarlary on the South Alligator River, 1984–1991

5.3 Kapalga

Extensive changes occurred at Kapalga on the South Alligator River between 1950 and 1991 (Fig 24). Of these changes, the most significant development since 1950 has been the extension of one main creek channel into a freshwater swamp, and subsequent saltwater incursion. In 1950, the invading channel appeared as a relatively indistinct creek with few first order tributaries, although it was linked to another creek. By 1975, both creeks had extended significantly (Fig 24). Growth occurred through bifurcation of the main tributary arms to form a small tributary network, and mangroves colonised a tributary linking the two creek channels.

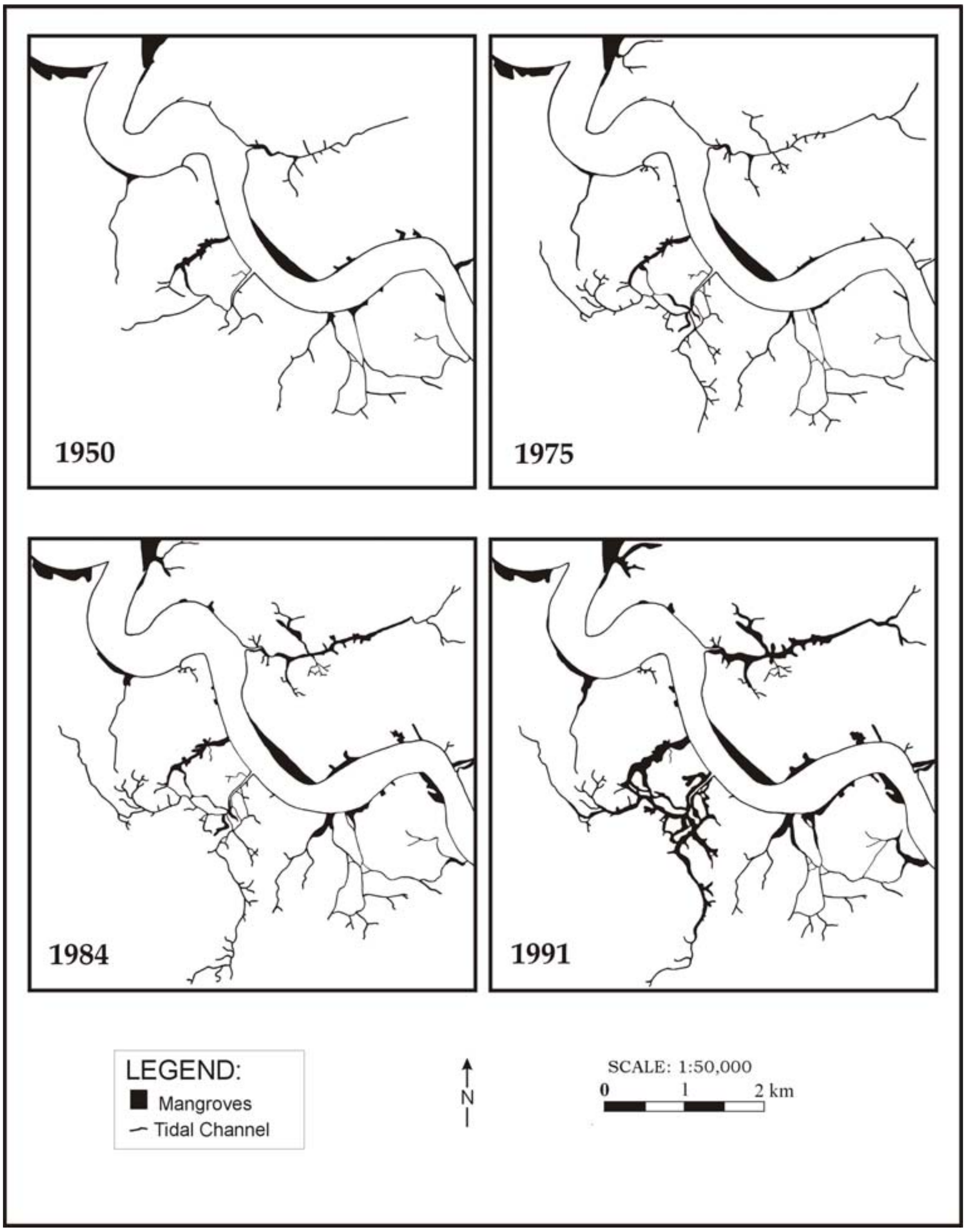

Figure 24 Tidal creek extension and the extent of mangrove encroachment at Kapalga on the South Alligator River, 1950–1991

By 1984, the southern channel had experienced rapid headward growth and invaded the low-lying wetland. Little further headward extension occurred by 1991, although rapid mangrove encroachment of the intruding channel and its tributaries was indicative of the expanding effects of saltwater influence.

The present distribution of the main morphological features at Kapalga supports observations of past changes from fresh to a saltwater phase. From 1950 to 1991, an intruding channel invaded the freshwater *Melaleuca* spp swamp south of the creek mouth, through a process involving headward extension of the tidal creek. Invasion of saltwater reduced the undulating swampland to salt flat and caused extensive dieback of the surrounding *Melaleuca* spp. Average electrical conductivity, based on 10 samples and obtained as a measure of the soil salinity of the salt flat at Kapalga was 3.21 mS/cm. Mangroves had densely colonised the tidal creek, and had encroached on most of the channel by 1991. Since that time, the mangroves have encroached further upstream and growth has intruded into areas of dead *Melaleuca* spp. Well-developed single mangroves in the upper reaches of the intruding creek are indicative of the current extent of the saltwater influence. Absence of new mangrove growth in the upstream part of the creek suggested that headward extension of the tidal creek was not continuing to occur at the rapid rate evident in the aerial photography from 1950 to 1991.

Field observations noted that the tidal part of the channel breached the upper limits of the tidal creek during high spring tide, inundating the surrounding undulating salt flat. The salt flat is characterised by dried cracked clay soils, overlain with desiccated fine sediment. The saltwater channel extended into areas of dead *Melaleuca* spp on the outskirts of the salt flat. This is testament to the processes of saltwater intrusion that had initially caused extensive *Melaleuca* spp. dieback. The large tidal range of 5–6 metres in Van Diemen Gulf induces strong bi-directional currents along the South Alligator River, with velocities sufficient for channel scouring (Knighton et al 1991). Although the impact of the large tidal range in the upper reaches is dampened, the incoming tidal front approached the upper limits of the Kapalga creek tributary at a significant rate of approximately 0.11 m/s during a high spring tide of 7 metres. The rate and extent of the tidal reach at Kapalga suggest that channel development and saltwater intrusion occur in response to tidal scour at this site. During exceptionally high tides, saltwater invades the surrounding plains, ponding in areas of slightly lower elevation and forming seepage zones. Through repeated tidal action, the seepage lines would eventually induce more efficient drainage and would subsequently become susceptible to channel incision.

6 Discussion and conclusions

Changes in the spatial characteristics and distribution of tidal creeks and mangroves in the Alligator Rivers Region over the past 50 years indicate that between 1950 and 1991 the zone of saltwater influence has expanded upstream. Although 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 spatial variation in the rates of change had not been determined in detail for the floodplains along the southern shore of Van Diemen Gulf. The research reported here has determined the spatial extent and rate of saltwater intrusion in the Alligator Rivers Region. This was done through compilation of maps of recent tidal creek extension and mangrove encroachment in the Wildman, West, South and East Alligator Rivers. The rapid rates of tidal-creek extension reported from the vicinity of the Mary River (Knighton et al 1992, Woodroffe & Mulrennan 1993) are now known to also apply to the wetlands of the Alligator Rivers Region. Saltwater incursion of freshwater wetlands has occurred along various reaches of the four Alligator Rivers Region rivers. The total area of freshwater wetland affected by saltwater intrusion is substantial. The area of greatest saltwater intrusion is that of the Mary River, with significant change also occurring to the floodplains of the South Alligator and East Alligator rivers.

The frequency of photography, with only 4 sets available, makes long-term detailed interpretation difficult, but provides information on the changes that have occurred between 1950 and 1991. Additionally, ground surveys at different locations along the estuary and river reaches indicate that there is a large degree of inter-annual variability between and within sites. It raises questions concerning the degree to which the three sites (Point Farewell, Munmarlary and Kapalga) provide good representation of headwater development of tidal creeks for the estuarine segments in which they occur. Nevertheless, observation of debris lines indicates that mudflats adjoining the estuarine funnel at each river are frequently and extensively inundated during the wet season and at high spring tides. In the dry season, the frequency of inundation appears to be lower and tidal activity higher, with distance upstream in the estuarine reaches of the rivers. The disparity between dendritic expansion of the low coastal mudflats and the single channel invasion of palaeochannels and floodplain basins is consistent with upstream change in estuarine hydrology and floodplain morphology.

At a broad scale, Knighton et al (1992) described environmental changes resulting from saltwater intrusion of the Mary River plains that are similar to those in the Alligator Rivers Region. Knighton et al (1992) determined that Sampan and Tommycut Creeks experienced exponential rates of growth that conform to trends observed in experimental networks. With the existing information it is difficult to identify a similar rate of growth on the eastern rivers, including Wildman River, South East and West Alligator Rivers, although the increase on them has been substantial.

It is likely that the semi-enclosed basin of Van Diemen Gulf, with its deep basin and broad nearshore shallows along the southern coast, amplifies the effects of northerly winds on water levels along the southern shore, along the coast of Chambers Bay and the Alligator Rivers Region. Drier than average wet seasons and strong monsoonal northwesterly winds would be associated with above average water levels in the southeastern Gulf, enhancement of tidal activity, and increased inundation of the coastal floodplains. A gradual, sustained increase in northerly winds has occurred over the recent historical period. Additionally, Point Farewell (Heerdeggen & Hill 2000) and Kapalga show evidence of *Melaleuca* spp. regrowth. These environmental changes may indicate that saltwater intrusion has and is occurring as part of the natural variability of the wetlands with the processes driving it contributing to raising the elevation of the floodplains through splay deposition at the headwaters of the tidal creeks. However, these hypotheses cannot be tested without detailed and long-term sea level observations from the Gulf, closer identification of the processes involved and examination of the patterns of vegetation regrowth at a site level.

Differences between the patterns of tidal creek intrusion in the Mary River and those occurring in the Alligator Rivers Region are apparent at a more detailed scale. 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 at its current phase of development.

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 limits of palaeochannels, This is consistent with observations by Knighton et al (1992) from the Mary River where pre-existing channels provided the principal routes for main channel extension. The preferential and rapid growth of tidal creek networks in these environments is indicative of the significance of slight topographical variations to the development of the creeks and the susceptibility of the palaeochannels to erosion.

Several authors, including Stocker (1970), Fogarty (1982) and Knighton et al (1992), drew attention to the impact of buffalo swim channels on saltwater intrusion of the Mary River coastal plains. The distribution of swim channels cut by buffalo in the Alligator Rivers Region has not been indicated on map compilations in this report showing recent changes in the pattern and extent of tidal creeks. Given the relationship observed between the main swim channels and tidal creek extension on the Mary River plains, it is likely that buffalo may have made some contribution to salt water intrusion in the Alligator Rivers Region where tracks and swim channels are noticeably lower than the surrounding floodplain and link adjacent palaeochannels. However, this is not always apparent either in the available aerial photography or on the ground. Buffalo swim channels are commonly oriented from one side of a palaeochannel to the other, across the direction of stream flow. Additionally, many tidal creeks, such as those near Point Farewell (Winn et al 2006) are initiated along the coastal margin of Van Diemen Gulf and in the estuarine funnel segment of the major rivers. These do not appear to have been prime habitats for buffalo. Further, the significance of the morphological impacts of buffalo compared to natural processes of environmental change, particularly the large-scale meteorological and oceanographic processes contributing to development of the floodplains, is open to question, as is the role of buffalo as a cause of salt water intrusion of the floodplains.

Despite variation in network expansion between the tidal rivers of the Alligator Rivers Region and its western neighbour, the Mary River flood plains, both areas have exhibited similar growth of salt water intrusion and mangrove colonisation. Future research should incorporate continued monitoring of changes, processes and rates of saltwater intrusion across the southern shores of Van Diemen Gulf and elsewhere in the Northern Territory. 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 either the processes of saltwater intrusion or its geographic distribution. 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 to the freshwater wetlands within the Alligator Rivers Region, and the high values of the wetlands for the Traditional Owners and wider community, establishment of a monitoring program based on current understanding of the response of the coastal lowlands to natural variability in sea level is a mandatory task for management. It could also be an important factor with the threat of sea level rise as a result of climate change.

Growth of tidal creek networks occurred in the eastern rivers of the Alligator Rivers Region, particularly the Wildman River and South Alligator River. It is possible that the semi-enclosed basin of Van Diemen Gulf, with its deep basin and broad nearshore shallows along the southern coast, amplifies the effects of northerly winds, particularly strong northwesterlies, on water levels along the southern shore. Drier than average wet seasons with strong onshore north westerly winds would be associated with above average water levels in the southeastern Gulf and enhancement of tidal activity on the flood plain surface. If this is so, then the changes observed along the southern shore would be geographically restricted and subject to reversal with a return to more average and higher rainfall conditions. The gradual, sustained increase in northerly winds over the historical period supports this argument. Additionally, Point Farewell and Kapalga show evidence of *Melaleuca* spp regrowth. This may indicate that saltwater intrusion has occurred as part of the natural variability of the wetlands and the processes driving it contributing to raising the elevation of the floodplains through splay deposition at the headwaters of the tidal creeks. However, these propositions cannot be tested without detailed analysis of the post 1991 satellite imagery and aerial photography now available; long-term sea level observations from the Gulf; and closer identification of the processes involved, including numerical modelling and examination of the patterns of vegetation regrowth at a site level.

It is not possible to demonstrate connections between the mechanisms described above, especially the coupling of floodplain development with atmospheric and oceanographic processes, without detailed long-term monitoring at appropriate geographic and temporal scales. Such monitoring is viewed as fundamental to an appreciation of interannual to interdecadal change in climate, sea level fluctuation and coastal response in the wet-dry tropics. Hence, in October 1996, the Environmental Research Institute of the Supervising Scientist, an office of the Commonwealth Government of Australia, initiated a program to assess and monitor coastal change in the Alligator Rivers Region of the Northern Territory (Eliot et al 2000). The program was supported until February 1998 as part of the core wetland research activities of the Institute but lapsed when the focus of the Institute changed. Nevertheless, the objectives of the monitoring program were to address processes that influence the stability and rate of change of the floodplain environments, in particular the switching between saline and freshwater systems with seasonal change from wet to dry conditions (Eliot et al 1999). These remain highly pertinent to any assessment of potential coastal impacts of projected climate change in northern Australia and assessment of risk arising from those changes.

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 regardless of the intensity of land use. 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. Observations of saltwater intrusion reported from the floodplains of southeastern Van Diemen Gulf provide a simple, descriptive summary of what has happened, and extends knowledge of the geographic distribution of saltwater intrusion in the Region. The observations also bring into question what might have caused saline intrusion and the adequacy of available information to assess changes in the landscape due to its natural variability.

References

Ahmad W & Hill GJE 1995. Land cover classification of the Mary River floodplain with emphasis on the effect of saltwater intrusion. *Proceedings of the 2nd North Australian Remote Sensing and GIS Forum*, eds Davenport CC, Riley SJ & Ringrose SM, Australian Government Publishing Service, Canberra, 76–83.

Bach C & Hosking EJ. 2002. *Wetland monitoring for the Mary River catchment, Northern Territory*. Natural Heritage Trust Project No. 97152, Department of Infrastructure, Planning and Environment, Darwin.

Bayliss B, Brennan K, Eliot I, Finlayson CM, Hall R, House T, Pidgeon R, Walden D & Waterman P 1997. *Vulnerability assessment of predicted climate change and sea level rise in the Alligator Rivers Region, Northern Territory Australia*. Supervising Scientist Report 123, Supervising Scientist, Canberra.

Bayliss P & Yeomans KM 1989. Distribution and abundance of feral livestock in the 'Top End' of the Northern Territory (1985–86), and their relation to population control. *Australian Wildlife Research* 16, 651–676.

Bell D, Menges C, Ahmad W & Van Zyl JJ 2001. The Application of dielectric retrieval algorithms for mapping soil salinity in a tropical coastal environment using airborne polarimetric SAR. *Remote Sensing* 75, 375–384.

Chappell J 1988. Geomorphological dynamics and evolution of tidal river and floodplain systems in Northern Australia, eds D Wade-Marshall & P Loveday *Northern Australia: Progress and prospects, Volume 2: Floodplains research.* Australian National University North Australia Research Unit, Darwin, 34–57.

Chappell JMA & Grindrod J 1985. Pollen analysis: A key to past mangrove communities and successional changes in northern Australian coastal environments. In *Coasts and tidal wetlands of the Australian monsoon region.* A collection of papers presented at a conference held in Darwin 4–11 November 1984, eds KN Bardsley, JDS Davie & CD Woodroffe, Australian National University, North Australia Research Unit, Darwin, 225–236.

Chappell J & Woodroffe CD 1985. Morphodynamics of Northern Territory tidal rivers and floodplains, In *Coasts and tidal wetlands of the Australian Monsoon Region*, eds KN Bardsley, JDS Davie & CD Woodroffe. Australian National University, North Australia Research Unit, Darwin, 85–96.

Chartres CJ, Walker PH, Willett IR, East TJ, Cull RF, Talsma T & Bond WJ 1991. *Soils and hydrology of Ranger Uranium Mine sites in relation to application of retention pond water.* Technical memorandum 34, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra.

Christian CS & Aldrick JM 1977. *Alligator Rivers Study: A review report of the Alligator Rivers Region Environmental Fact Finding Study*. Australian Government Publishing Service, Canberra.

Clarke MF, Wasson RJ & Williams MAJ 1979. Point Stuart chenier and Holocene sea levels in northern Australia. *Search* 10, 90–92.

Clarke RL & Guppy JC 1988. A transition from mangrove forest to freshwater wetland in the monsoon tropics of Australia. *Journal of Biogeography* 15, 665–84.

Coleman JM & Wright LD 1978. Sedimentation in an arid macro-tidal alluvial river system: Ord River, Western Australia. *Journal of Geology*. 86, 621–42.

Davie JDS 1985. The mangrove vegetation of the South Alligator River, Northern Australia. In *Coasts and tidal wetlands of the Australian monsoon region*, eds KN Bardsley, JDS Davie & CD Woodroffe, Australian National University North Australia Research Unit, Darwin, 53–62.

Department of Defence 2002. *Australian National Tide Tables.* Australian Hydrographic Publication 11. Australian Government Publishing Service, Canberra

Duggan K 1985. Erosion and sediment transport in the lowlands of the Alligator Rivers Region, Northern Territory. In *Coasts and Tidal Wetlands of the Australian Monsoon Region*, eds KN Bardsley, JDS Davie & CD Woodroffe, Darwin, Australian National University North Australia Research Unit, 53–61.

Duggan K 1988. Mining and erosion in the Alligator Rivers Region of northern Australia. PhD Thesis, School of Earth Sciences, Macquarie University.

East TJ 1996. Landform evolution. In *Landscape and vegetation ecology of the Kakadu Region, Northern Territory,* eds CM Finlayson & I von Oertzen, Kluwer Academic Publishers, Dordrecht, The Netherlands, 37–55.

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.

Ellison JC 1993. Mangrove retreat with rising sea-level, Bermuda. *Estuarine, Coastal and Shelf Science* 37, 75–87.

Ellison JC & Stoddart DR 1991. Mangrove ecosystems collapse during predicted sea-level rise: Holocene analogues and implications. *Journal of Coastal Research* 7, 151–165.

Erskine WD & Saynor MJ 2000. *Assessment of the off-site geomorphic impacts of uranium mining on Magela Creek, Northern Territory, Australia*. Supervising Scientist Report 156, Supervising Scientist, Darwin NT.

Finlayson CM & Woodroffe CD 1996. Wetland vegetation In *Landscape and vegetation ecology of the Kakadu Region, Northern Territory*, eds CM Finlayson & I von Oertzen, Kluwer Academic Publishers, Dordrecht, The Netherlands, 81–112.

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

Fogarty P 1982. *A preliminary survey of environmental damage associated with activity of feral buffalo.* Conservation Commission of the Northern Territory, Darwin.

Fox RW, Kelleher GG & Kerr CB 1977. *Ranger Uranium Environmental Inquiry*, Second Report, Australian Government Publishing Service, Canberra.

Gray W 1975. *Tropical cyclone genesis*. Department of Atmospheric Science Paper No 234, Colorado State University, Fort Collins, Colorado.

Green, T 1996. The dynamics of Van Diemen Gulf. Honours Thesis in Environmental Engineering, Centre for Water Research, University of Western Australia, Crawley.

Heerdegen RG & Hill JE 2000. Freshwater to saltwater: Rapid saline intrusion, East Alligator River, Kakadu National Park, In *Conference Proceedings: 20th New Zealand Geography Conference*, eds Roche M, McKenna M & Hesp P, New Zealand Geographical Society, Palmerston.

Hegerl EJ, Davie PJF, Claridge GF & Elliot AG 1979. *The Kakadu National Park mangrove forests and tidal marshes, A review of the literature and results of a field reconnaissance to the Australian National Parks and Wildlife Service.* Vol 1, Canberra.

Hope G, Hughes PJ & Russell-Smith J 1985. Geomorphological fieldwork and the evolution of the landscape of Kakadu National Park. In *Archaeological research in Kakadu National Park*, ed R Jones, Australian National Parks and Wildlife Service, Canberra 229–240.

Jolly P & Chin D 1992. Rehabilitation of the Mary River floodplains: A review of MSS and TM imagery 1972–1992., In *Proceedings of the GIS and Environmental Rehabilitation Workshop*, eds Davenport CC, Riley SJ & Ringrose SM, Australian Government Publishing Service, Canberra, 43–54.

Kench PS 1999. Geomorphology of Australian estuaries: Review and prospect. *Australian Journal of Ecology* 24, 367–380.

Kingston D 1991. Hydrology of the northern wetlands. In *Monsoonal Australia: Landscape, ecology and man in the northern lowlands*, eds CD Haynes, MG Ridpath & MAJ Williams, AA Balkema, Rotterdam, 31–35.

Knighton AD, Mills K & Woodroffe CD 1991. Tidal-creek extension and saltwater intrusion in Northern Australia. *Geology* 19, 831–34.

Knighton AD, Woodroffe CD & Mills K 1992. The evolution of tidal creek networks, Mary River, Northern Australia. *Earth Surface Processes and Landforms* 17, 167–190.

Lees BG 1987. Age structure of the Point Stuart Point Chenier Plain: A reassessment, *Search* 18, 257–259.

Lowry J & Riley J 2004. Assessing density and distribution change in paperbark trees on the Magela floodplain, Kakadu National Park using Geographic Information Systems (GIS). *Supervising Scientist Note* April 2004.

Mc Bride J & Keenan T 1981. Climatology of tropical cyclone genesis in the Australian region. *Journal of Climatology* 2, 13–33.

McQuade C, Arthur J & Butterworth I 1996. Climate and hydrology of the Kakadu Region. In *Landscape and vegetation ecology of the Kakadu Region, northern Australia*, eds CM Finlayson & I von Oertzen, Kluwer Academic Publishers, Dordrecht, The Netherlands, 17–36.

Mitchell W, Chittleborough J, Ronai B & Lennon G 2001. Sea level rise in Australia and the Pacific, in *Proceedings of the Pacific Islands Conference on climate change, climate variability and sea level rise, linking science and policy*, eds M Grzechnik & J Chittleborough, Flinders Press, Adelaide. 13–19.

Moliere DR 2007. Preliminary analysis of streamflow characteristics of the Tropical Rivers Region. Internal Report 519, February, Supervising Scientist, Darwin. Unpublished paper.

NCCOE 2004. *Coastal engineering guidelines for working with the Australian coast in an ecologically sustainable way*. National Committee on Coastal and Ocean Engineering, Engineers Australia, Canberra.

Nanson GC, East TJ, Roberts RG, Clark RL & Murray AS 1990. Quaternary evolution and landform stability of Magela Creek catchment, near the Ranger Uranium Mine, northern Australia. Open file record 63, Supervising Scientist for the Alligator Rivers Region, Canberra. Unpublished paper.

O'Neil GC 1983. An investigation of recent geomorphological change on a section of the South Alligator River floodplain, Kakadu National Park. Report to the Australian National Parks and Wildlife Service, Canberra:

Pariwono J, Bye J & Lennon G 1986, Long-period variations of sea-level in Australasia. *Geophysical Journal of the Royal Astronomical Society* 87, 43–54.

Rayment GE & Higginson FR 1992. *Australian laboratory handbook of soil and water laboratory methods.* Inkata Press, Melbourne.

Rhodes EG 1980. Modes of Holocene coastal progradation, Gulf of Carpentaria. PhD thesis. Australian National University, Canberra.

Rhodes EG 1982. Depositional model for a chenier plain, Gulf of Carpentaria. *Sedimentology* 29, 201–221.

Roberts RG 1991. Sediment budgets and quaternary history of the Magela Creek catchment, Tropical Northern Australia. Open file record 80, Supervising Scientist for the Alligator Rivers Region, Canberra. Unpublished paper.

Russell-Smith J 1985. A record of change: studies of Holocene vegetation history in the South Alligator region, Northern Territory. *Proceedings of the Ecological Society of Australia* 13, 191–202

Ryan D, Heap A, Radke L & Heggie D 2003. *Conceptual models of Australia's estuaries and coastal waterways. Applications for coastal resource management*. Geosciences Australia Record 2003/09, Canberra.

Schumm SA, Mosley MP, & Weaver WE 1987. *Experimental fluvial geomorphology*. John Wiley, New.York.

Semeniuk V 1994. Predicting the effect of sea-level rise on mangroves in North-western Australia. *Journal of Coastal Research* 10 (4), 1050–1076.

Shreve RL 1967. Infinite topologically random networks. *Journal of Geology* 75, 178–186.

Stocker GC 1970. The effects of water buffaloes on paperbark forest in the Northern Territory. *Australian Forest Research* 5, 29–34.

Story R, Williams MAJ, Hooper ADL, O'Ferral RE & McAlpine JR 1969. *Lands of the Adelaide-Alligator area, Northern Territory*. CSIRO Land Research Series 25, CSIRO, Melbourne.

Vertessy RA 1990. *Morphodynamics of macrotidal rivers in far north Australia*, PhD thesis, Australian National University, Canberra.

Walden DJ 2000. Surface hydrology of the Alligator Rivers Region. Paper 5. In *Assessment and monitoring of coastal change in the Alligator Rivers Region, northern Australia*, eds

Eliot I, Saynor M, Eliot M & Finlayson CM 2000. Supervising Scientist Report 157, Supervising Scientist, Darwin, 70–90.

Wasson RJ (ed) 1992. *Modern sedimentation and late Quaternary evolution of the Magela Creek plain*. Research report 6, Supervising Scientist for the Alligator Rivers Region, AGPS, Canberra.

Wells AG 1985. Grouping tidal systems in the Northern Territory and the Kimberley Region of Western Australia on presence/absence of mangrove species. In *Coasts and tidal wetlands of the Australian monsoon region*, eds KN Bardsley, JDS Davie & CD Woodroffe, Australian National University North Australia Research Unit, Darwin, 119–132.

Williams AR 1984. Changes in Melaleuca forest density on the Magela floodplain, Northern Territory, between 1950 and 1975. *Australian Journal of Ecology* 9, 199–202.

Winn KO, Saynor MJ, Eliot MJ & Eliot IG 2006. Saltwater intrusion and morphological change at the mouth of the East Alligator River, Northern Territory. *Journal of Coastal Research* 22(1), 137–149.

Wolanski E & Chappell J 1995. The response of tropical Australian estuaries to a sea level rise. *Journal of Marine Systems* Vol 7, 267–279.

Woodroffe CD 1995. Response of tide-dominated mangrove shorelines in Northern Australia to anticipated sea-level rise. *Earth surface processes and landforms* 20, 65–85.

Woodroffe CD, Chappell JMA, Thom BG & Wallensky E 1985a. Stratigraphy of the South Alligator tidal river and plains, Northern Territory. In *Coasts and tidal wetlands of the Australian monsoon region.* A collection of papers presented at a conference held in Darwin 4–11 November 1984, eds KN Bardsley, JDS Davie & CD Woodroffe, North Australia Research Unit, Australian National University, Darwin, 17–30.

Woodroffe CD, Chappell JMA, Thom BG & Wallensky E 1985b. Geomorphology of the South Alligator tidal river and plains, Northern Territory. In *Coasts and tidal wetlands of the Australian monsoon region.* A collection of papers presented at a conference held in Darwin 4–11 November, 1984, eds. KN Bardsley, JDS Davie & CD Woodroffe. North Australia Research Unit, Australian National University, Darwin, 3–15.

Woodroffe CD, Chappell JMA, Thom BG & Wallensky E 1986. *Geomorphological dynamics and evolution of the South Alligator River and plains, Northern Territory.* North Australia Research Unit, Australian National University, Darwin.

Woodroffe CD, Chappell JMA, Thom BG & Wallensky E 1989. Depositional model of a macrotidal estuary and floodplain, South Alligator River, Northern Australia. *Sedimentology* 36, 737–756.

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

Woodroffe CD, Mulrennan ME & Knighton AD 1991. Geomorphology of the Mary River Plains, NT: An interim Report. Unpublished report to the CCNT.

Woodroffe CD, Thom BG & Chappell JMA 1985c. Development of widespread mangrove swamps in mid-Holocene times in Northern Australia. *Nature* 317, 711–713.

Woodroffe CD, Thom BG, Chappell JMA, Wallensky E, Grindrod J & Head J 1987. Relative sea level in the South Alligator River region, North Australia during the Holocene, *Search* 18, 198–200.