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Channel extension and the geomorphology of tidal creeks in Kakadu National Park, Northern Territory

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supervising scientist

CHANNEL EXTENSION AND THE GEOMORPHOLOGY OF TIDAL CREEKS IN KAKADU NATIONAL PARK, NORTHERN TERRITORY

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Sinuous meanders of the South Alligator River.

ABSTRACT

The aim of this thesis is to determine the rate, spatial extent and geomorphological character of saltwater intrusion in Kakadu National Park, northern Australia. Intrusion of saltwater into freshwater wetlands through the process of tidal-creek extension has been identified as the major coastal management problem in the Alligator Rivers Region and adjacent areas. This research acts as a facet of the Coastal Monitoring Program already existing at the Environmental Research Institute of the Supervising Scientist. Research methods were employed to document the coastal changes associated with saltwater intrusion of the Alligator Rivers Region. The progress of tidal creek extension and mangrove encroachment of the Wildman, West, South and East Alligator Rivers of the eastern Alligator Rivers Region was reconstructed from aerial photographs for the years 1950, 1975, 1984 and 1991 at a scale of 1:100,000. Specific sites were chosen from the different stream sections identified by Chappell (1988) for more detailed examination of evidence of saltwater intrusion. Detailed maps were constructed of the specified sites from aerial photographs at 1:25,000 and field surveys were mapped using a Global Positioning System.

Changes in the spatial characteristics and distribution of the tidal creeks and mangroves in the eastern Alligator Rivers Region indicate that the saltwater reach has expanded along extending creek lines since 1950. Tidal creek growth has 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 and East Alligator Rivers. Mangrove growth has increased at an exponential rate for the four river systems. Collation of field data suggested that different processes of saltwater intrusion are dominating the different field sites. This research has completed the current understanding of the extent of saltwater intrusion of the wider Alligator Rivers Region in Van Diemen Gulf.

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CHAPTER 1 : SALTWATER INTRUSION IN KAKADU NATIONAL PARK

1.1 AIM

The aim of this thesis is to determine the rate, spatial extent and geomorphological character of saltwater intrusion in Kakadu National Park, northern Australia. Saltwater intrusion has occurred through tidal-creek extension over the past 50 years in the western Alligator Rivers Region (Knighton *et al.*, 1991; 1992; Woodroffe and Mulrennan, 1993) and it is highly likely that it has occurred in the eastern Alligator Rivers Region, including the floodplains of Kakadu National Park.

1.2 CONTEXT

Intrusion of saltwater, through tidal-creek extension into the freshwater meadows and billabongs of low-lying floodplains has been identified as the major coastal management problem in the Alligator Rivers Region and adjacent areas (Bayliss *et al.*, 1995). In coastal and near-coastal areas of low tidal range (Figure 1.1), freshwater wetlands may be lost to saltwater incursion through a gradual disintegration process in response to localised relative sea-level rise (Day *et al.*, 1991). The low-lying marsh-dominated islands of Chesapeake Bay, United States, are currently experiencing rapid rates of relative sea level rise of approximately 3 mm/yr (Downs et al., 1994). This is resulting in land loss through gradual submergence of the islands, including the formation of interior ponds (Figure 1.1). Alternately, in areas of large tidal range, rapid tidal-creek extension represents the dominant mechanism of saltwater intrusion. In this context it poses a major threat to the natural freshwater flora and fauna of the macro-tidal coastal wetlands of Kakadu National Park (Bayliss *et al.*, 1995; Knighton *et al.*, 1991; 1992).

The Alligator Rivers Region, which incorporates Kakadu National Park as its eastern component, was one of eight regions assessed in 1995 by the Department of Environment, Sports and Territories (DEST) program on Vulnerability to Predicted Climate Change and Sea-level Rise. Within this assessment, predicted and observed implications of shoreline recession and saltwater intrusion on both the salt and freshwater wetland resources of the Alligator Rivers Region were outlined. Shoreline recession will result in a reduction of some components of the mangrove fringe on the coastline, and saltwater intrusion has been associated with accompanying mangrove colonisation along the saline creek lines (Bayliss *et al.*, 1995). Saltwater intrusion into freshwater resources is predicted to manifest in a loss of freshwater

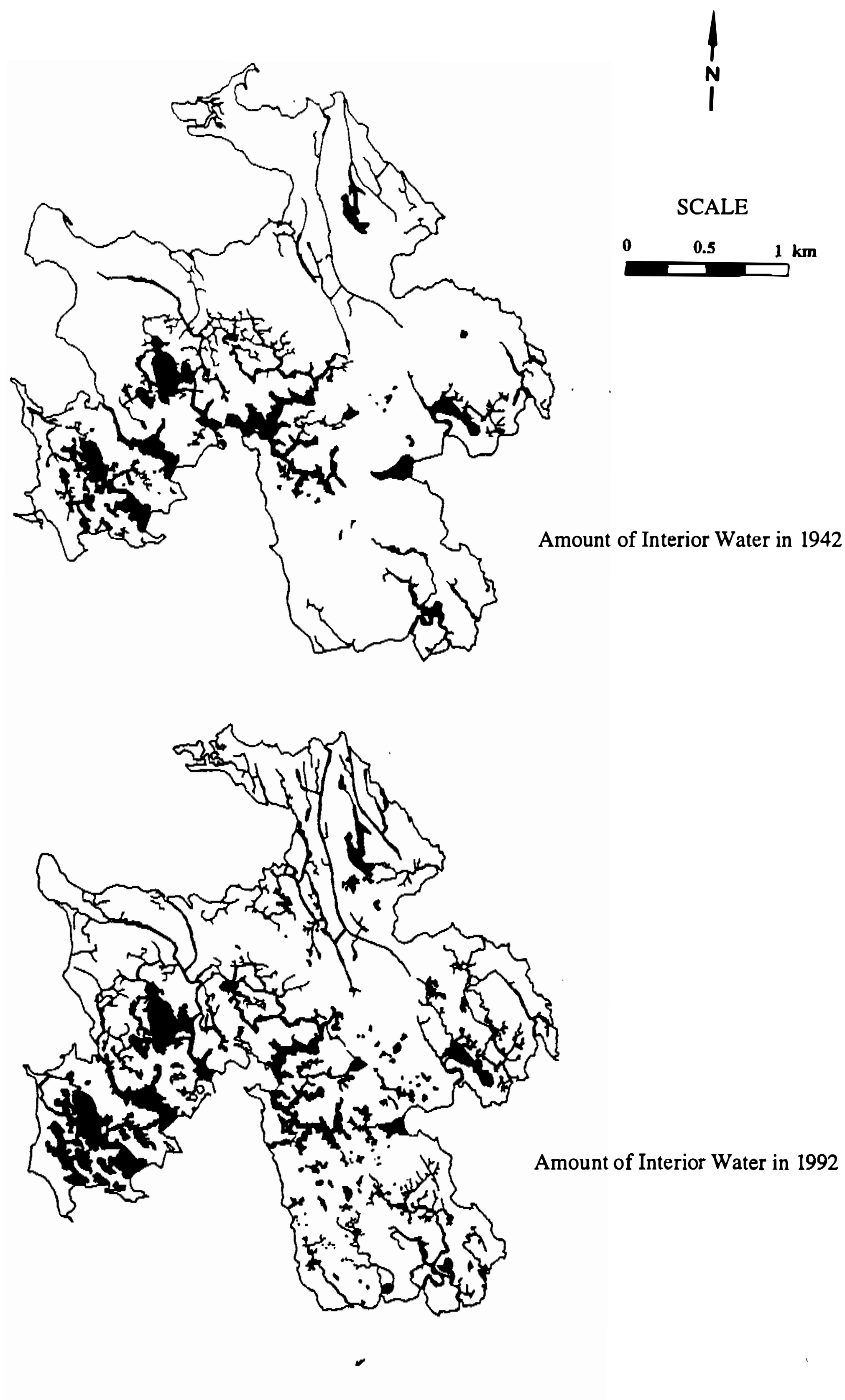


FIGURE 1.1 : Drainage and pond expansion on Bloodsworth Island, Chesapeake Bay, 1942 - 1992 (Downs *et al.*, 1994).

vegetation of some wetlands, and the replacement of freshwater wetlands with saline mudflat (Bayliss *et al.*, 1995).

A monitoring program to record the processes and rates of saltwater intrusion was identified as an essential task for management. This would exist as a facet of the Coastal Monitoring Program already existing at the Environmental Research Institute of the Supervising Scientist (*eriss*). The underlying rationale of the recommendation was that it would be feasible to employ spatial information management tools to delineate areas of risk, once the processes of saltwater intrusion through tidal-creek extension are thoroughly understood, and both the rate of growth and spatial extent of tidal-creek extension in the Alligator Rivers Region have been determined. The research undertaken for the purposes of this Honours thesis was conducted in response to recommendations of the vulnerability assessment.

1.2.1 Significance of the Wetlands in Kakadu National Park

Kakadu National Park covers a total area of approximately 20 000 km^2 (Figure 1.2). It is the largest terrestrial national park in Australia (Finlayson, 1995). Approximately thirteen percent of the park area, around 2 600 km^2, is comprised of seasonally inundated coastal and estuarine wetlands. In this respect it is the largest remaining area of freshwater wetlands in Australia (Finlayson, 1995). The wetlands of Kakadu National Park support a unique combination of cultural, social and natural resources which are a major attraction for park visitors, and have hence established the park as a major tourist destination for Australian and International tourists.

Kakadu National Park is one of only seventeen sites world-wide which have been included for both natural and cultural values in the World Heritage properties established under the international Convention Concerning the Protection of the World Cultural and Natural Heritage (Finlayson, 1995). The significance of the wetlands as a natural resource relates to the unique extensive ecological diversity of both the natural flora and fauna, which has been described as both unique and representative (Finlayson, 1995). The floodplains of the northern coast include important wildfowl breeding sites, and the river systems support a diverse variety of fish and other aquatic species (Knighton *et al.*, 1991). Essentially, the freshwater wetland resources give the social and economical importance to Kakadu National Park as a site of natural and cultural significance. A growing tourist industry drives the economic significance of the wetlands. Expenditure on visits to Kakadu National Park currently accounts for more

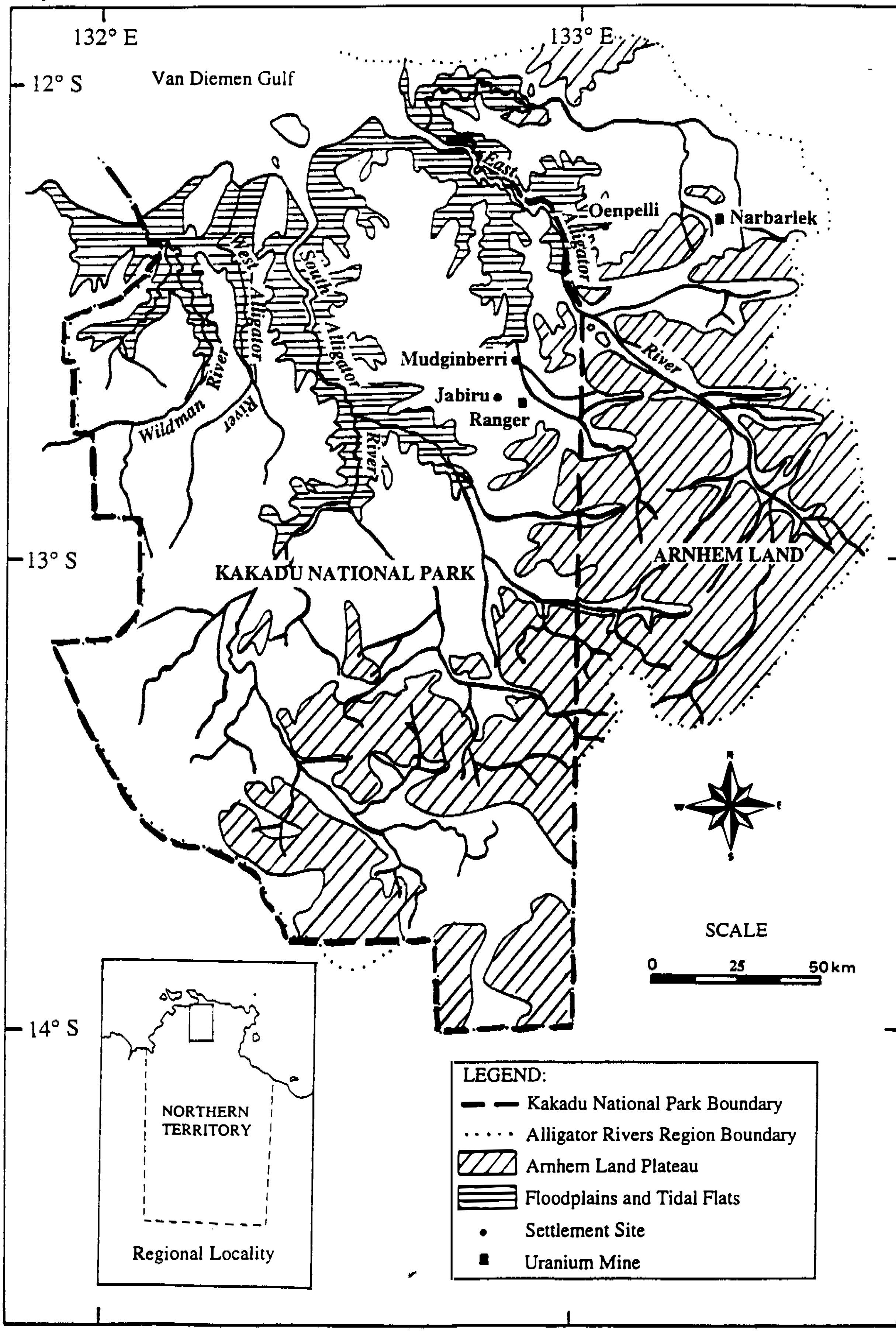


FIGURE 1.2 : Locality Map of Kakadu National Park

Regional and geomorphological setting of Kakadu National Park within the eastern Alligator Rivers Region. Adapted from Duggan K., 1985 and Wasson, R.J. (ed.), 1992.

than 25% of the total expenditure produced directly from tourism within the Northern Territory (Finlayson, 1995). In addition to the wetlands attraction of visitors, the social significance of the river systems is linked to the popularity of the freshwater recreational fisheries of the northern coast.

Floodplain development varies across the Alligator Rivers Region, from Darwin to the Coburg Peninsula (Figure 1.3). The western Alligator Rivers Region is comprised of closed dendritic tidal creek systems, including Tommycut and Sampan creeks. In contrast to these rivers, the South and East Alligator Rivers of the eastern Alligator Rivers Region are open estuarine river systems. Research addressing the problems associated with saltwater intrusion through tidal creek extension have already been conducted and documented for the western Alligator Rivers Region (Knighton *et al.*, 1991; 1992; Woodroffe and Mulrennan, 1993). Given the geomorphological variation of the floodplains in the eastern Alligator Rivers Region, Kakadu National Park, it is an essential task for management to extend the scope of monitoring and research to include the floodplains of Kakadu National Park.

1.3 ENVIRONMENTAL SETTING

1.3.1 Climate

Kakadu National Park, within the Alligator Rivers Region catchment, is located in the wet-dry tropics of northern Australia, between latitudes 12°S and 14°S, and flanking Van Diemen Gulf some 120 km east of Darwin (Figure. 1.2). The climate of the northern coast of Australia is monsoonal, with a highly seasonal rainfall regime that defines two distinct seasons (Woodroffe *et al.*, 1986). The Wet season commences late in the year (November - December) when relatively low atmospheric pressures develop over northern Australia and induce a pressure gradient, causing an inflow of warm air from the surrounding tropical ocean (Lee and Neal, 1984). Monsoonal troughs and tropical cyclones directly related to monsoon activity are the dominant rain producing systems. The result is a hot and rainy season that lasts for three to four months, although both the onset and duration may fluctuate from year to year (Lee and Neal,

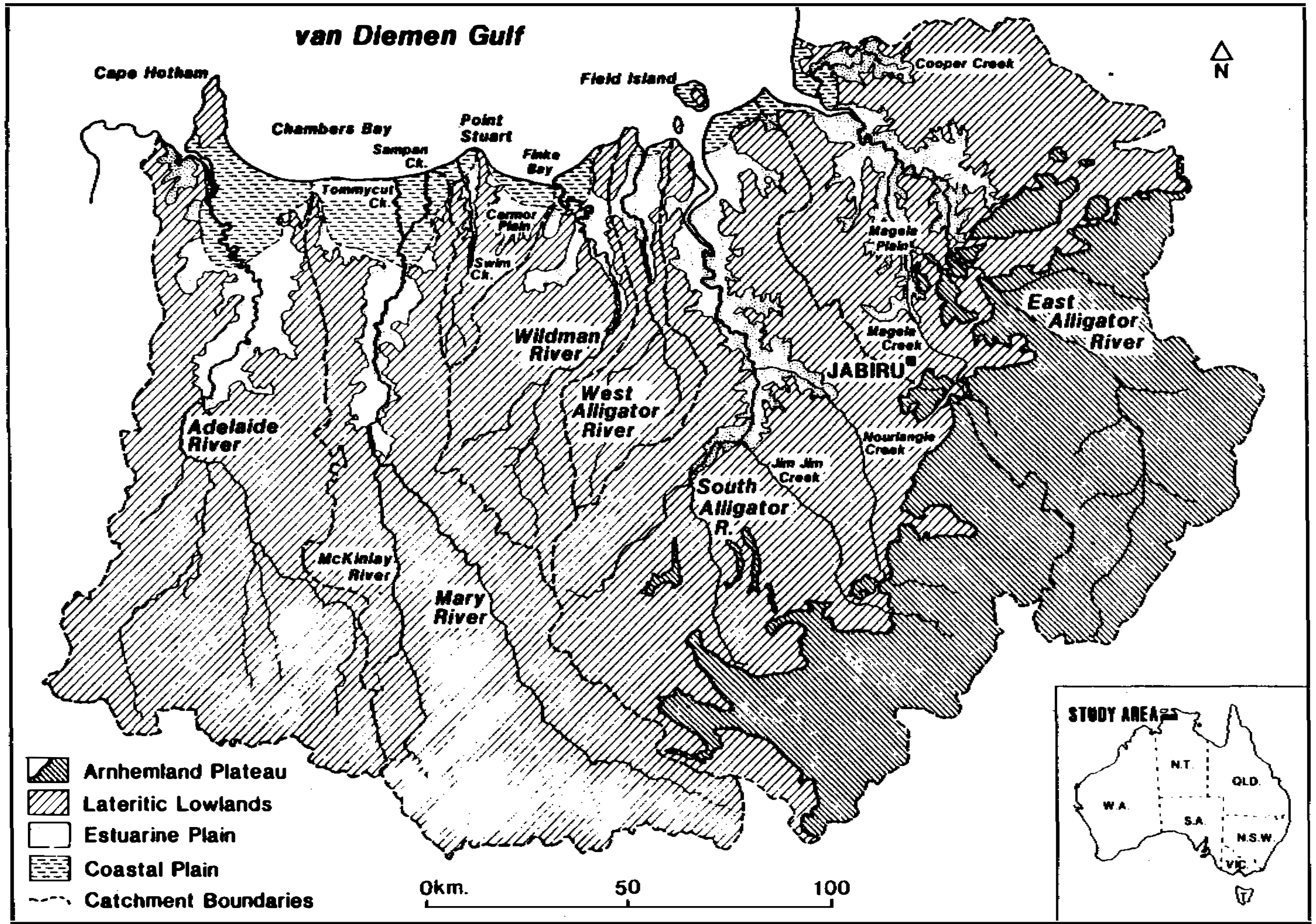


FIGURE 1.3 : Locality Map of the wider Alligator Rivers Region
(Woodroffe and Mulrennan, 1993).

1984). In contrast to this, very little rain falls during the Dry season months, from May to September.

The average annual rainfall of the region between Darwin and the Alligator Rivers Region is between 1300 and 1600 mm, with rainfall almost totally confined to the months of the Wet (Whitehead *et al.*, 1990). The rainfall regime does not appear to vary greatly in seasonality or amount from region to region, although the rainfall amount that does fall in the Dry is more variable than that during the Wet (Taylor and Tulloch, 1985). The monsoonal climate is characterised by warm to hot temperatures throughout the year, accompanied by high relative humidities of about 80% (Lee and Neal, 1984). Mean daily minimum and maximum temperatures for the Alligator Rivers Region are 19.2°C and 30°C in July (the Dry season), and 25.2°C and 33.1°C in November at the onset of Wet (McAlpine, 1976). The pronounced seaonality of the climate may be a significant factor to the regional vulnerability to saltwater intrusion, as the prolonged Dry season is conducive to saltwater ingress (Woodroffe and Mulrennan, 1993).

1.3.2 Hydrology

Characteristic of the coastline of north and north-western Australia, the Alligator Rivers Region is drained by a series of large tidal rivers. The South Alligator River is the largest of the four main river systems within the Alligator Rivers Region catchment, with a catchment area extending over about 9000 km^2 (Woodroffe *et al.*, 1986). Lateritic coastal and estuarine floodplains flanking the river systems are near-horizontal progradational plains, with elevations less than five metres above Australian Height Datum (Wasson, 1992). Their elevation is close to maximum spring tide, which is approximately 6 metres above Australian Height Datum. The low gradient of the plains, coupled with the large tides of the Alligator Rivers Region, enables the tidal influence to penetrate over 100 km up the river system (Woodroffe *et al.*, 1986). However, the flow hydrology of the river systems is highly seasonal, in response to the pronounced seasonality of the monsoonal rainfall regime upon the tidal-floodwater interface.

At the beginning of the Dry season, the freshwater runoff discharge declines with completion of the Wet season rainfall and, as the season advances, eventually ceases. The freshwater meadows evaporate and shrink to small ponds. In the streams tidal flows then dominate over the floodwaters, and the tidal reach of the rivers becomes increasingly saline and well mixed (Woodroffe *et al.*, 1986). At the onset of the Wet season, the floodstage increases up to eight metres in wetter years. Estuarine reaches of the rivers become predominantly fresh (Woodroffe and Mulrennan, 1993). The flood peak generally rises with minor reversions, due to the high freshwater discharges of rainfall runoff, reaching a maximum peak flow of approximately 400-700 cubic metres per second around April. It causes extensive flooding of the adjacent low-lying plains, predominantly from overbank flow (Woodroffe *et al.*, 1986, Woodroffe and Mulrennan, 1993). The floodwater dominance over the tidal upstream flow of saltwater induces the development of a saltwedge. The estuarine reach of the river remains stratified until late in the Wet season when the rainfall runoff from the catchments gradually recedes, and the Dry season tides again begin to dominate over the floodwater discharge (Woodroffe *et al.*, 1986).

1.3.3 Soils

Soils of the seasonally inundated estuarine and coastal floodplains are uniform fine-textured clay soils (particles < 0.002 mm) (Woodroffe and Mulrennan, 1993). The two soil types which dominate the coastal plains are black, massive clays of the Wildman family, and the massive or weakly self-mulching clays of the Carmor family over estuarine muds which are found in the wetter parts of the plains (Woodroffe *et al.*, 1986). Saline clays of the Carpentaria family underlie the bare salt flats characteristic of saltwater seepage zones.

The textural and structural characteristics of the coastal floodplain soil relates to the seasonal climate and hydrology. Sedimentation of finer sediments within river channels and on surrounding floodplains occurs at periods of high river flows (Nanson and Croke, 1992). This is a feature of the monsoonal wet season floods. Fine sediment then dries to desiccation during the Dry season, breaking into polygonal cracks, often more than 50 cm deep (Plate 1.1). Given this, the structural and textural characteristics of sediment, may provide an indication of the active processes of sedimentation and erosion occurring on the floodplains. This may be applied to understanding the processes of tidal creek extension in the vicinity of tidal creek headwaters during the Dry season.

1.3.4 Floodplain Development

Stratigraphic evidence on the coastal plains of the South Alligator, Adelaide and Mary River plains, which lie adjacent to Kakadu National Park, have provided an indication of the morphodynamic processes operating on the northern coast of Australia (Knighton *et al.*, 1991, Woodroffe *et al.*, 1986). Preliminary radiocarbon and thermoluminescence data, based on the

PLATE 1.1: Black cracking clays
Melaleuca spp. dieback area overlying the desiccated cracking clays of the Kapalga saltflats, South Alligator River, with evidence of polygonal cracks in the foreground.

existence of shallow mangrove sediments and shoreline deposits in the stratigraphic record, suggest that the freshwater wetlands of the floodplains in the Alligator Rivers Region have developed only in the last few thousand years (Woodroffe *et al.*, 1989; 1993).

Stratigraphic sections based on drillholes have indicated the sea level was rising before it stabilised within a few metres of its present position around 6 000 BP (Woodroffe *et al.*, 1987). Sedimentation near the margins of the deepening estuaries had kept pace with sea level rise and stable shorelines gradually accumulated tidal deposits. Once the sea level had stabilised, mangrove forest spread widely throughout the estuaries, a period termed the 'Big Swamp' (Chappell, 1988). The coastal plains then began intensive progradation. This was a period of construction and accretion, with episodic chenier formation, during which the most rapid deposition occurred from 5 000 years to 3 000 years BP (Woodroffe *et al.*, 1986, Woodroffe and Mulrennan, 1993). Since around 3 000 BP the coastal plain has been prograding at a decelerating rate, with evidence of little depositional activity since 2 000 BP (Woodroffe *et al.*, 1986, Woodroffe and 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 progradational period. Whilst the timing over the change is not known exactly, radiocarbon dating of shell middens indicated that some regions of the South Alligator River floodplains had changed by 4 000 years BP (Woodroffe *et al.*, 1986). Whilst the plains of northern Australia have changed markedly over the last 6 000 years of the Holocene (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.

1.4 SALTWATER INTRUSION IN THE ALLIGATOR RIVERS REGION

Recognition of the increasing content of carbon dioxide and other gases within the earth's atmosphere has lead to varying predictions of coastal changes anticipated to be caused by the enhanced global greenhouse conditions. In particular, there has been widespread concern that global warming may accelerate the rate of sea level rise, from expansion of oceans and partial melting of ice sheets, snow fields and glaciers (Hoffman, 1984; Pearman, 1988). This concern has lead to the development of numerous deterministic process models which attempt to predict the implications of future coastal climate and sea level changes. The main anticipated consequences of a rise in sea-level relative on the coast of northern Australia have been predicted for tidal river estuaries, largely in response to depth-averaged tidal models that utilise the full, non-linear equations of motion (Chappell *et al.*, 1996). Anticipated outcomes include increased flooding of the coastal floodplains, and saline water penetration into freshwater deltaic and estuarine areas (Bayliss *et al.*, 1995). Extreme predictions indicate that a return to the Big Swamp phase is possible (Chappell, 1988). Evidence of recent tidal creek extensions, and the problems associated with the intrusion of saltwater into freshwater environments, have been observed and described within the literature for a number of the major rivers within the Alligator Rivers Region and adjacent areas. Results from the wider Alligator Rivers Region provide a comparative base for the investigation of the Kakadu wetlands.

1.4.1 Evidence of Saltwater Intrusion

The Mary River is one of the series of north Australian rivers that drain into van Diemen Gulf. Yet unlike the estuarine river systems that are characteristic of the Alligator Rivers Region, the Mary River catchment is drained by a series of dendritic tidal creeks that bifurcate from the sea (Knighton *et al.*, 1991). Since the late 1930s and early 1940s, two of the tidal creeks of the

Mary River catchment, Tommycut and Sampan Creek, have extended headward from the coast, breached the chenier ridge barrier that runs sub-parallel to the coastline, and developed a network of tidal tributaries extending over 30 km inland (Knighton *et al.*, 1991).

Knighton *et al.* (1991) reconstructed the progress of network expansion of Tommycut and Sampan Creek since 1943, in detailed maps drawn from 1943, 1950, 1963, 1973, 1980, 1989 and 1991 aerial photographs under x 8 magnification (Figure 1.4). Given that the aerial photographs varied in both scale and quality for each year, mapping was standardised to ensure comparability between dates (Knighton *et al.*, 1992). Each tributary was assigned a number and a set of rules based on the differences between consecutive dates to determine the presence and absence of each stream. The creek system mapped from 1991 aerial photography, indicating the pattern of extension and contraction since 1989, is illustrated in Figure 1.5.

As evident in Figure 1.4, the most remarkable feature of the Mary River floodplains is the rapidity with which the tidal network has developed. In 1943, the two main creeks had breached the coastal chenier ridge, yet extended no further than 5 km inland. By 1991, the network of tidal creeks and their tributaries had drainage densities as high as 10 km/km^2 (Knighton *et al.*, 1991). The expansion of the tidal creek network, measured by its magnitude, has been exponential, and has resulted in reimposing 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 comparison of 1950 and 1983 aerial photography, Woodroffe *et al.* (1986) identified evidence of recent tidal creek extensions on the South Alligator River floodplains in the Alligator Rivers Region (Figure 1.6). In the upstream and cuspate segments of the river, several tidal creeks have lengthened and extended headwards towards freshwater wetlands of the floodplains. Whilst the figure inset on Figure 1.6 indicates that there has been tidal creek extension on the sinuous segment of the river, and local extension of creeks of the estuarine funnel, the potential threat of the expanding creeks of the upper reaches of the river are the subject of most concern. From comparison of the 1950 and 1983 aerial photographs Woodroffe et al. (1986), Fogarty (1982) and O'Neil (1983) identified notable changes on the South Alligator River indicative of an increasing saltwater influence. The location of mangrove

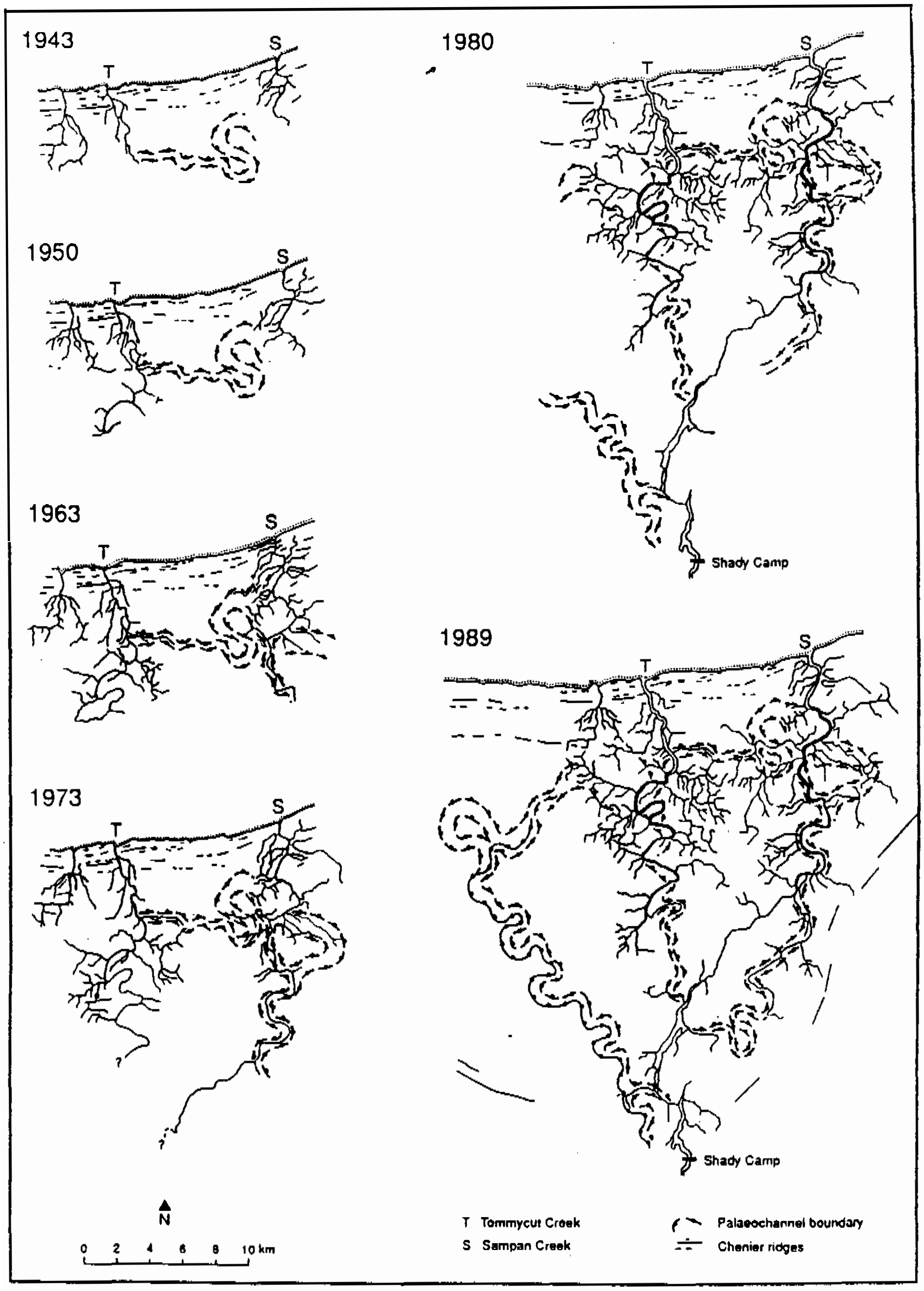


FIGURE 1.4 : Expansion of Sampan and Tommycut Creeks, Mary River, 1943 - 1989 (Knighton *et al.*, 1992).

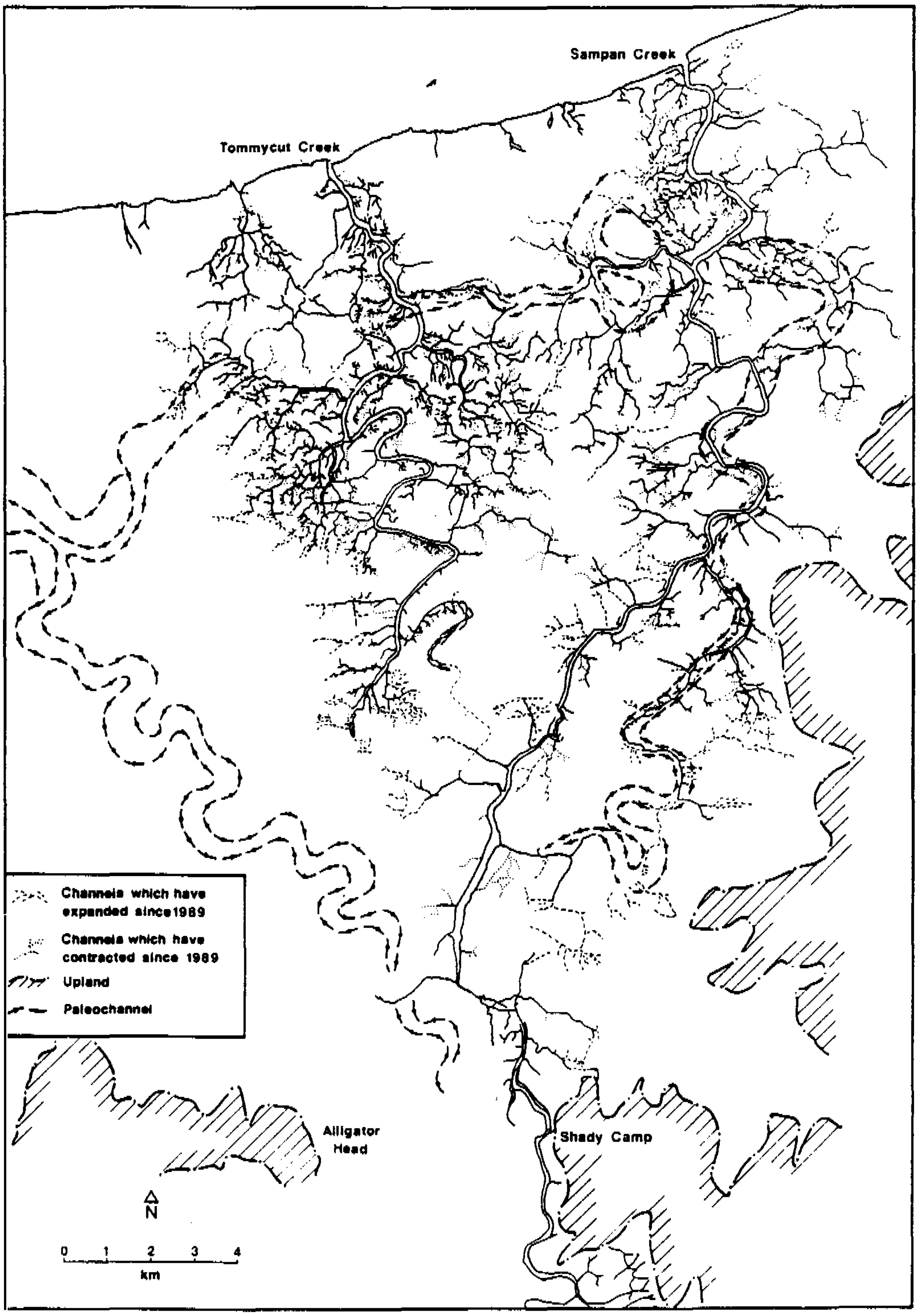


FIGURE 1.5 : Expansion of Sampan and Tommycut Creeks, Mary River, 1989-1991 (Knighton *et al.*, 1992).

extensions along creeklines that have become more tidally active (Section 1.4.4) and in areas where there has been expansion of upper intertidal and salt mudflats reflective of tidal inundation, are illustrated on Figure 1.6. Their observations additionally noted areas of dead *Melaleuca spp.* swamp as evidence of saltwater intrusion into freshwater billabongs and swamps via the extending tidal creeks. Similar observations of *Melaleuca spp.* dieback have been observed on the Magela creek system of the East Alligator (Williams, 1984). From comparison of aerial photographs taken in 1950 and 1976, 38% of the perineal freshwater forest, dominantly *Melaleuca spp.*, which covered almost 60% of the floodplain in 1950, suffered significant tree 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.

Observations of the modes of tidal channel evolution on the Mary River by Knighton *et al.* (1992), indicate that tidal channels develop though a combination of an extension and widening of the main channels and tributary growth. The process of tidal channel formation reportedly begins with overbank flooding or the surface invasion of saltwater over the floodplains during an exceptionally high tide. The saltwater penetrates the freshwater floodlines in areas that lie lower in elevation than the levees of the tidal channels, resulting in the formation of seepage zones close to the channel headwaters. Whilst at this stage the floodlines are relatively indistinct and shallow, with a high width to depth ratio, the central part of the seepage zone is scoured through repeated tidal action. Subsequently, the initially diffusive flow along the floodline becomes increasingly concentrated, the floodline becomes incised and the result is a more efficient drainage path through the channels. Stream incision is rapid, especially in those channels that drain directly into the major creeks. Knighton *et al.* (1992) suggests this to be due to the proximity to large semidiurnal fluctuations in base level. Floodwaters of the Wet season may act to accentuate the process of tidal scour.

1.4.2 Contributing Factors

From observations of the geomorphological and hydrological characteristic features of the floodplains, and the spatial distribution pattern of Sampan and Tommycut creeks, Knighton *et al.* (1992) suggested that several factors have contributed to the vulnerability of the Alligator Rivers Region and adjacent areas to the extension of tidal channels. These factors warrant further field survey and closer examination. 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-

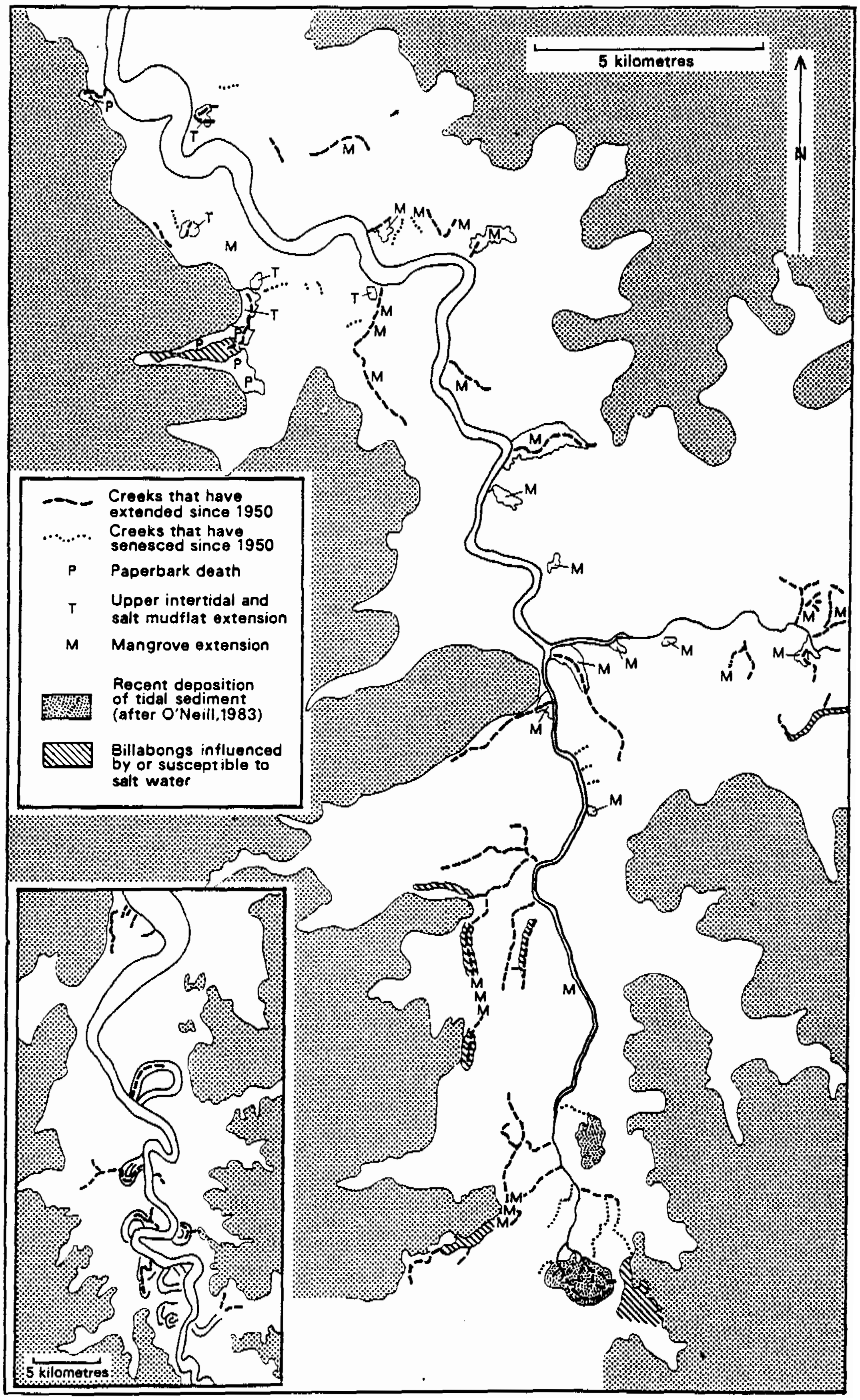


FIGURE 1.6 : Recent changes and tidal creek extension of South Alligator River, 1950 - 1983 (Woodroffe *et al.*, 1986).

directional currents with high velocities within the tidal influence of channels, and hence a high potential for tidal scouring (Knighton *et al.*, 1991).

Elevations of the Alligator Rivers Region coastal plains are less than five metres above mean sea level, and much of the Mary River floodplains are around two metres elevation. Substantial regions of the coastal plains are at elevations below this (Woodroffe and Mulrennan 1993). Many of the remote backwater plains lie at or below the elevation reached by the highest tides, 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 very low gradient of the low-lying floodplains of the coastal and estuarine regions of the northern coast emphasises the degree to which the floodplains are vulnerable to be quickly exploited by invading saltwater channels, or are likely to become evaporative ponds in the Dry following overbank flooding during the Wet season.

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

1.4.3 Possible Causes of Recent Tidal Creek Extension

Despite extensive research conducted on the Mary River floodplains and the Alligator Rivers, there has been no single causal explanation identified to account for the extension of tidal influences over the past approximate 50 years. Rather, saltwater intrusion has been attributed variedly within the literature. This suggests that the change in the balance of the tidal systems, from a predominantly freshwater environment to an environment dominated by saltwater conditions, is actually a combination of a number of influential factors (Woodroffe and Mulrennan, 1993).

The direct impact of large numbers of uncontrolled feral buffalo on the erosion of tidal channels has attracted significant attention within the literature. It is a commonly held view that buffalo have hastened, if not initiated, the extension of tidal influences. From an examination of aerial photographs (1950-1981), Fogarty (1982) noted a correlation between the extent of saltwater intrusion and an increase in buffalo on the floodplains. Similar observations have been made on the South Alligator River floodplains (D. Lindner pers. comm.; cited in Finlayson *et al.*, 1988). Buffalo grazing and trampling along channel heads and banks has caused breakdown of levees and expansion of existing channels in some circumstances (Fogarty, 1982; Stocker, 1970). Extensive erosion channels have formed along buffalo swim-channels on the South Alligator River plain, dissecting levees and connecting salt and freshwater environments (D. Lindner pers. comm.; cited in Finlayson et al, 1988).

Whilst the buffalo numbers have declined in recent years largely due to the spread of Brucellosis (Woodroffe and Mulrennan., 1993), an estimation of 341,000 animals were present within the lower Mary River plains during 1985. This is a density of approximately 1.53 buffaloes per square kilometre (Bayliss and Yeomans, 1989). Furthermore, high production values of buffalo hide in the 1930s to 1940s suggest that buffalo numbers were particularly high around the period when the creek networks of both the Mary and South Alligator Rivers began to erode. Since the 1970's, 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 removal of the buffaloes and the reclamation work, 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.).

Woodroffe and Mulrennan (1993) identified the present pattern of tidal creek extension and salt water intrusion as a reinvasion of the low-lying coastal and palaeoestuarine plains that were once at an elevation above which saltwater could reach. Given that much of the wetland that previously excluded saltwater is now well below the highest spring tide level, then either an increase in the elevation of the high tide level, or a lowering of the plains has occurred. Woodroffe *et al.* (1991) stated that any net change of sea level appears to be negligible (Cited in Woodroffe and Mulrennan, 1993). Suggestions have been made that compaction and consolidation of the sediments since their deposition have caused the change (Woodroffe and Mulrennan, 1993). Material is compressed by weight of overlying sediments and subsidence is recognised within deltaic estuaries supporting this claim (Woodroffe and Mulrennan, 1993). The rate of consolidation or compaction is unknown. However, it has been recognised that progressive consolidation and compaction would explain the lower heights evident of the western levee and palaeochannel surface, comparative to the eastern palaeochannel of the Mary River floodplains (Woodroffe and Mulrennan, 1993).

As an alternative proposition, Woodroffe *et al.*, (1986) suggested that changes in tidal amplitude throughout the rivers of northern Australia, during their evolution since the big swamp phase, may be linked with evidence of recent salt invasion. The elevation of spring high tide water level will increase if a tidal river becomes shorter through meander cutoff, and shallower through shoal formation (Chappell, 1988) In this context recent channel expansion may be a response to the long term change in geomorphology. Both these changes have occurred in the South Alligator River in the last few thousand years, and it is likely to have occurred in the East Alligator in the same period.

Research on the South Alligator River by Woodroffe *et al.* (1986) indicated that the river morphology has become wider and shallower through the cuspate segment since its prior sinuous phase in morphological evolution. Additionally, the present morphology of the South Alligator River is shorter than the former channel due to meander cutoff and without meander regrowth (Chappell, 1988). Between 50 and 75 km upstream the channel is now a series of cuspate bends which are wider, shallower and less sinuous than the meander loop of the palaeo river which existed previously. Woodroffe *et al.*, (1986) also indicate that the palaeo river was deeper than the present cuspate bends. The shortening, shallowing and widening which occurred on the South Alligator River is expected to have increased the spring high tide by about 0.5 to 1 metre in the upstream reaches of the South Alligator tidal river (Woodroffe *et al.*, 1986).

Not all the rivers of the northern coast have evolved in the same way as the South Alligator. However, Chappell (1988) suggests that all probably flowed though sinuous meandering channels at the time of their floodplain formation, around 5 000 years ago. Subsequent changes of river morphology, and hence tidal amplitudes, are therefore likely to be a reflection on the sizes of their catchments and of their floodplain and tidal river systems (Chappell, 1988).

The trends of saltwater intrusion are generally well known from the published literature on the South Alligator and Mary River floodplains. However documented observations are incongruent, and in some cases inconclusive. Maps of the distribution and spatial extent of tidal creeks and mangroves for the different regions differ in scale and format, and hence are not directly comparable. Subsequently, the geographic extent of the implications of saltwater intrusions, the spatial variation in the rates of change, and the area of wetlands affected by saltwater intrusion have not been determined in detail. Additionally, the mechanics of tidal creek extension are largely unknown. The research undertaken for the purposes of this Honours thesis addresses these aspects. This research is an initial step to the identification and documentation of areas at risk, as well as the changes that have occurred over the past 50 years in Kakadu National Park. It completes our understanding of the extent of saltwater intrusion of the wider Alligator Rivers Region in van Diemen Gulf.

1.4.4 Changes in Mangrove Distribution

Mangroves are halophytic trees or shrubs that are almost entirely restricted to the upper intertidal zone. They are characterised by adaptations to unconsolidated, periodically inundated, saline coastal habitats (Woodroffe, 1995). Mangrove communities existing within Kakadu National Park form narrow bands along the coast and on tidally influenced creek and river banks, with the most extensive development occurring in areas associated with freshwater influences (Stanton, 1975). Given that the young, unconsolidated substrates of mangrove shorelines are continuously exposed to daily tidal oscillations and seasonal flooding, they are naturally unstable or dynamic environments, extending or contracting rapidly in response to relative sea-level changes (Woodroffe, 1995). This recognition has lead to suggestions that the structure and distribution of mangrove communities may be associated with the tidal creek extensions of saltwater influence into freshwater wetlands of the Alligator Rivers Region (Woodroffe *et al.*, 1986; Bayliss *et al.*, 1995). The proposition is further examined in this dissertation.

Spatial variations in the distribution of mangroves along the estuarine river systems of the Northern Territory coastline have been investigated relatively extensively within the literature, 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 and Woodroffe, 1995). Past research has documented supportive evidence of a close relationship between mangroves and sea-level fluctuations (Woodroffe, 1987; Ellison and Stoddart, 1991; Ellison, 1993; Semeniuk, 1994). Given this, mangrove sediments have been identified as indicators of former sea-level. Radiocarbon dating of mangrove wood fragments of the South Alligator River has been indicative of sea level changes dating over the past 6 000 years (Woodroffe, 1987).

Generally, mangroves are well known from the published research of mangrove ecosystems and characteristics to be sensitive indicators of changes in relative sea-level and salinity regimes. Subsequently, the spatial extent and patterns of mangrove encroachment along tidal creeks of the Alligator Rivers Region, may be indicative of the processes and extent of saltwater intrusions within the region. Although detailed recommendations have been outlined, there is no previous record of a long-term monitoring program of mangroves within the Alligator Rivers Region (Bayliss *et al.*, 1995). Subsequently, the spatial extent, rates and trends of mangrove growth have not been determined. Given this, the present research determines changes in mangrove distributions along the tidal channels and creeks of Kakadu National Park, as a indicator of the trends of saltwater intrusion.

1.4.5 Morphology and Tidal hydrodynamics

The macro-tidal estuaries of the Alligator Rivers Region, including the Daly and South Alligator Rivers, are composed of four morphological channel elements typical of a tidal river system (Chappell and Woodroffe, 1985); an estuarine funnel, sinuous and cuspate meanders and an upstream reach (Figure 1.7). The estuarine funnel is broad at the mouth, diminishing upstream in width negative-exponentially, and often featured with one or more large dog-leg bends. The funnel passes upstream into a series of regular, sinuous meanders. Cuspate meanders lie upstream from the sinuous bends and are characterised by sharp points on the inside of each bend, clearly distinguishable from the asymmetrical bends in the sinuous meander segment of the river. The cuspate meanders often have shoals near each point, otherwise broad mid-channel shoals may be present. The upstream segment of the estuarine river has irregularly spaced bends, which differentiate the upstream from the regularity of the

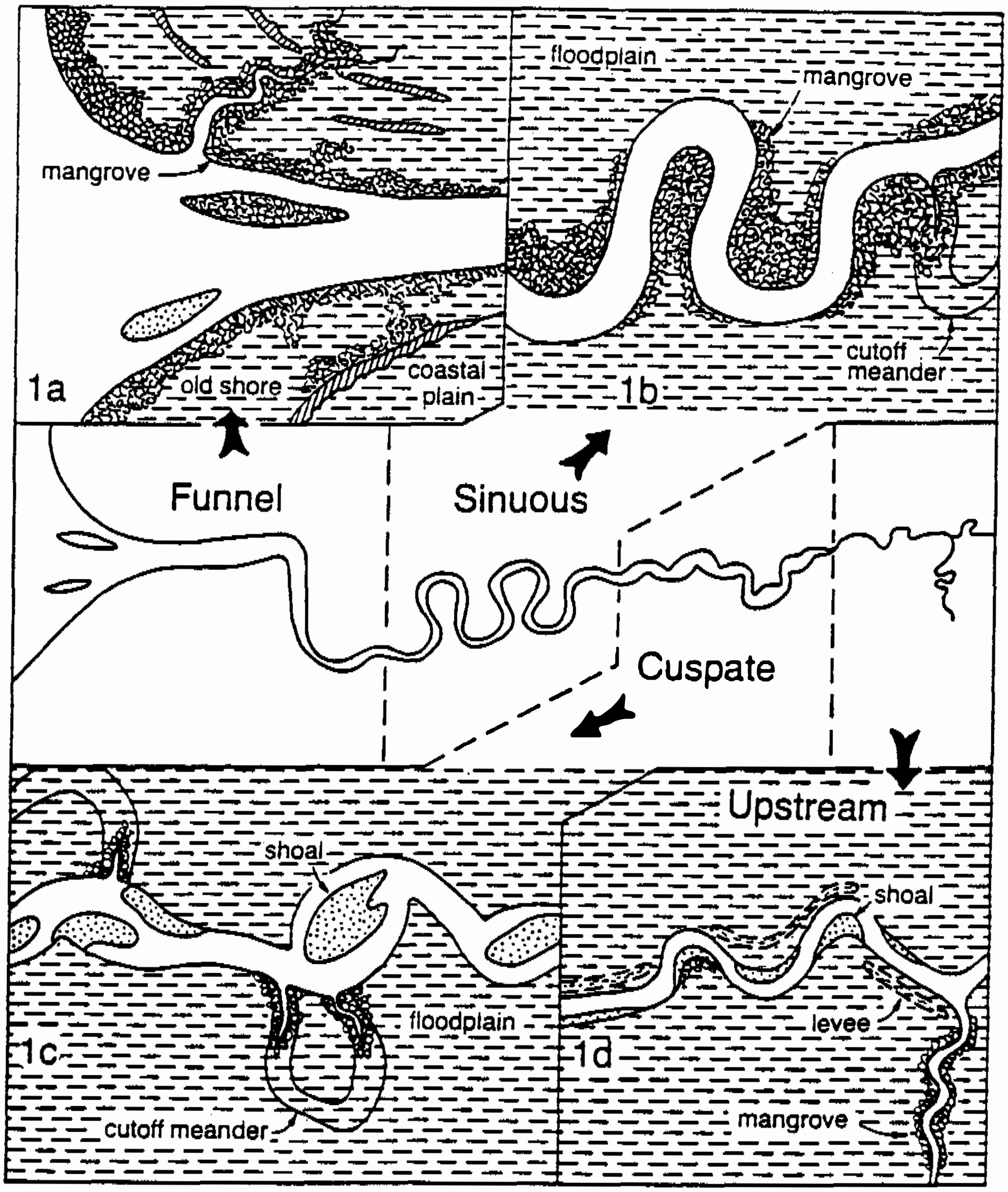


FIGURE 1.7 : Schematic tidal river showing the characteristics of different river segments (Chappell *et al.*, 1988).

meander segment. Channel width is significantly narrower and deeper in the upstream segment than the cuspate meanders further downstream.

Chappell and Woodroffe (1985) 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. The transition area of an estuarine channel where the sinuous or cuspate bends meet the upstream segment was determined to be near the point where the mean annual flood peak discharge approximately equals the peak upstream flow or dry season spring tides (Chappell and Woodroffe, 1985). Alternately, the transition from the funnel to the sinuous segments of the channel occurs where the peak spring tide flow is roughly ten times the mean annual flood peak discharge (Chappell and Woodroffe, 1985). The sinuous section of the river is the locus of active meander migration, where freshwater flood discharges exceed the flood tidal flows (Vertessy, 1990). Within the cuspate segments, however, the flood tidal flow is roughly equal to the seasonal freshwater flood discharge.

The variation in the tidal/freshwater interface for the four segments demonstrate that the dominating hydrological processes vary over the stream sections of a river estuary. The relationships outlined indicate that the transit time for water and sediment is rapid in the upstream segment during the Wet season flooding, whereby freshwater rainfall discharge is high and the tidal impedance to floodwaters is negligible in this segment (Chappell and Woodroffe, 1985). In contrast to this, water and sediment transit through the sinuous meanders of the river channel into the estuarine funnel is slow, due to the dominating tidal flows restraining the floodwaters (Chappell and Woodroffe, 1985).

The relationship between the channel hydrological processes and the stream sections identified may be significant to understanding the mechanics of saltwater intrusion. Fogarty (1982) noted that the estuarine systems have a component of natural instability due to the small differences in elevation between the salt and freshwater environments, the close proximity of the two environments and the constant movement and interaction of water and sediment during the Wet season. The variation in tidal hydrodynamics of each stream segment suggest that different processes dominate the different regions. That is, processes that may contribute to saltwater intrusion, specifically tidal, overbank wash, or fluvial processes differ between each segment. Given these observations, this research project aims to identify evidence of differing hydrological processes of saltwater intrusion dominating at the extending tidal creeks of each channel segment. This project therefore acts as a step to the identification of the processes of saltwater intrusion occurring within Kakadu National Park during the Dry season.

1.5 STATEMENT OF OBJECTIVES

Establishment of the rate, spatial extent and trends of saltwater intrusion requires the compilation of information relating to the growth rate and distribution patterns of tidal creek extension and mangrove encroachment, as an indicator of the extent of saline influence. The broader aim of this research will be achieved through following more specific objectives. These are to:

1. map the tidal channels of Kakadu National Park 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, extent and character of tidal creek expansion within Kakadu National Park, of the Alligator Rivers Region,
3. determine the rate, extent and character of mangrove encroachment within Kakadu National Park, of the Alligator Rivers Region;
4. identify and describe the component micromorphologies of land surface units in the vicinity of the headwaters of tidal creeks in the different stream sections identified by Chappell *et al.*, (1988); and
5. where appropriate, compare changes in the Kakadu National Park with those that have occurred in the wider Alligator Rivers Region over the same time period.

CHAPTER 2 : RESEARCH METHODOLOGY

2.1 OVERVIEW

The research methods employed to document the coastal changes of the Alligator Rivers Region may be separated into four congruent sections. The first part of the research involved interpretation from aerial photographs and topographical maps to reconstruct the general pattern of tidal creek and mangrove expansion in the Alligator Rivers Region. Specific sites were chosen for more detailed examination of evidence of saltwater intrusion. These were selected on the basis of preliminary observations from the 1:25,000 aerial photograph interpretation and discussions with *eriss* staff familiar with the changing environment. Detailed maps of tidal creek and mangrove changes of the selected sites were constructed from aerial surveys and from the collation of field survey and mapping data. The field surveys included application of Global Positioning System (GPS) techniques (ASHTECH equipment and Reliance software). Processed field mapping data was converted into a Geographic Information Systems (GIS) format for mapping purposes. Laboratory and qualitative analysis techniques were utilised to determine the rates and topological properties of the changes observed. The details of these steps have been outlined below.

2.2 MAPPING OF GENERAL CHANGES IN THE DISTRIBUTION OF TIDAL CREEKS AND MANGROVES

The progress of tidal creek expansion and mangrove encroachment of the Wildman, West, South and East Alligator Rivers of the eastern Alligator Rivers Region, was reconstructed from detailed maps drawn from aerial photographs for the years 1950, 1975, 1984 and 1991. The aerial photographs were flown during the Dry season of each year. This aided determination of the tidal reach of the creeks, as the creek tidal flows dominate over the freshwater floodwaters at this time. Although the photographs were seasonally consistent, they varied in scale and quality (Table 2.1). This instigated a problem of ensuring comparability between the dates.

To overcome this, mapping of tidal creeks was standardised in a manner consistent with that used by Knighton *et al.* (1992). Taking the most recent photograph set as the standard (1991), each tributary was assigned an identification number on the basis of stream order. The presence

TABLE 2.1 : Details of Aerial Photography

Date of photography	Scale	Height (m)	Colour	Quality*
May 1950	1:50,000	7620	black and white	3
June 1975	1:25,000	3810	colour	1
May 1984	1:25,000	un-defined	colour	2
May 1991	1:25,000	3962	colour	1

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

or absence of each numbered creek for the years mapped was determined by a set of rules devised by Knighton *et al.* (1992) for the Mary River. A creek that was present on consecutive sets of photographs was included when mapping. A creek that was absent from the middle of one of three consecutive sets, but present on the others was regarded as present on all three dates. Similarly, a creek that was present on the middle of three consecutive sets of photographs, but absent on the others was regarded as absent on all three dates. Knighton *et al.* (1992) noted that the latter of these conditions particularly affected the largest and best quality photographs, whereby many of the smallest tributaries were excluded. This particular condition has not posed a problem in this study, as the most detailed photographs, 1975, 1984 and 1991, were the same scale and of similar quality (Table 2.1).

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 aid comparison of the presence or absence of streams. Overlays also enabled the comparison of the length and topologic properties of the tidal creeks, and the spatial distribution pattern of mangroves.

2.3 SITES FOR MORE INTENSIVE EXAMINATION

Specific sites were chosen for more detailed examination of the characteristics and trends of saltwater intrusion. Sites were selected from the South and East Alligator Rivers for the different stream segments identified by Chappell (1988). Selection of sites from the estuarine funnel, sinuous and cuspate segments of the rivers was in response to a number of informal selection criteria. Identification of suitable field sites was initially based on preliminary observations of tidal-creek and mangrove extensions from the aerial photograph interpretation. Discussions with *eriss* wetland protection and management staff drew attention to suitable sites for field mapping and ground survey work from a local knowledge of areas exhibiting evidence of saltwater intrusion. Given the time and practical restrictions on fieldwork in the remote areas of Kakadu National Park, site accessibility was a significant factor to be taken into consideration.

Examination of the selected sites incorporated detailed mapping of the tidal creek and mangrove changes from aerial photographs. Sources of the aerial photography used are detailed in Appendix 1. The progress of tidal creek expansion and mangrove encroachment at each site was reconstructed from maps drawn from aerial photographs for the four years, 1950, 1975, 1984 and 1991. Maps were compiled at a working scale of 1: 25,000, with particular attention given to detail, as the length and area properties of creeks and mangroves were the subject of analysis (see Section 2.5).

Three field sites were selected on the basis of the above criteria, to be mapped in detail as a baseline for future measurement and assessment of geomorphologic change. The geomorphological setting and rationale for individual site selections are outlined below.

2.3.1 Point Farewell

Site Point Farewell is located on the southern coastline of the East Alligator River estuarine funnel (Figure 2.1), approximately 2 km south-east of Point Farewell peninsula. The site was selected due to the processes of saltwater intrusion evident on the estuarine funnel segment of the tidal river system. Examination of aerial photographs for the years 1950 to 1991, as outlined above, revealed evidence of localised rapid tidal creek and mangrove extensions in the vicinity of the area (Plate 2.1). Remote sensing projects investigating the use of satellite imagery to predict the trends of saltwater intrusion are currently operating in conjunction with *eriss*. Point Farewell has been used for preliminary studies. The research described herein documents the present site morphology and potential change of field sites, in addition to the changes which have occurred in the recent past. The data attained from this research may therefore provide ground truthing information significant as a baseline for future measurement and assessment.

2.3.2 Munmarlary

Site Munmarlary is located on the transition from the funnel to the sinuous bends of the South Alligator River, 30 km upstream from the river mouth (Figure 2.1). The sinuous segment of the river generally occurs where the freshwater flood discharges exceed the flood tidal flows.

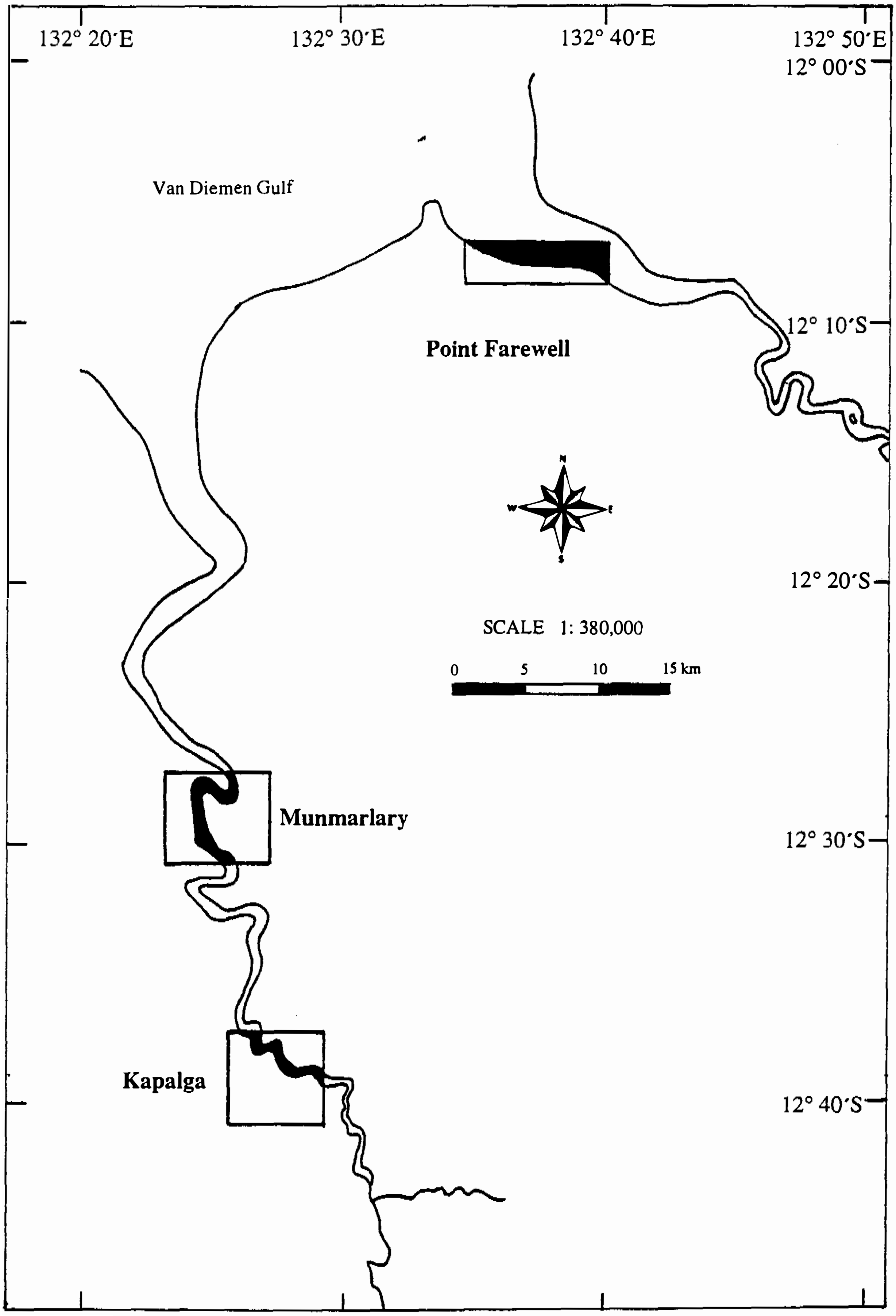


FIGURE 2.1 : Locality Map of Study Sites, Munmarlary, Kapalga and Point Farewell

Source: Base map information is correct to 1971, adapted from Australian 1:100,000 Topographic Survey maps, Series R621, published by the Royal Australian Survey Corps, 1976.

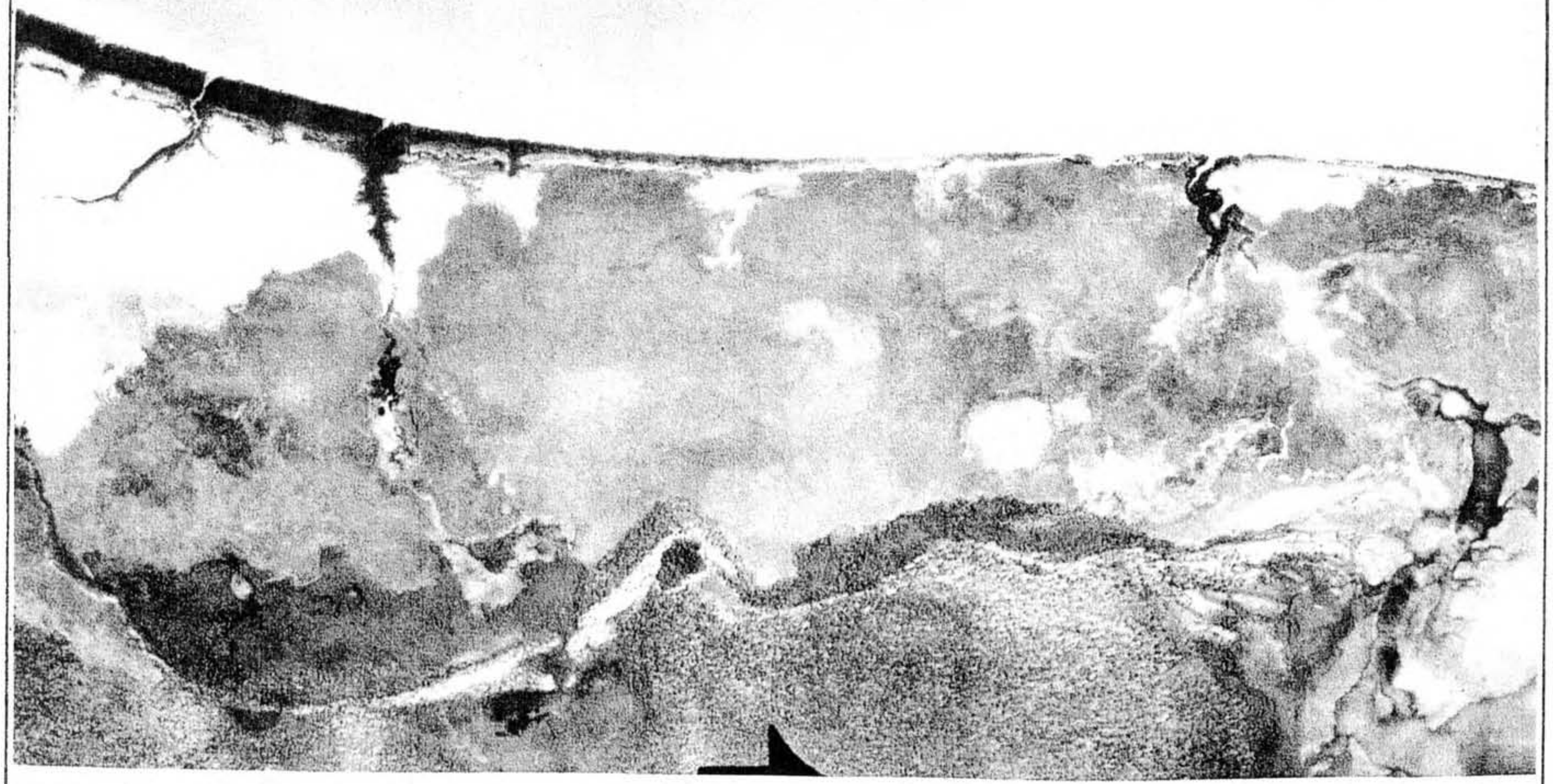


PLATE 2.1a: Aerial photograph of Point Farewell, East Alligator River, 1950.

Photographic evidence of tidal creek extension and mangrove colonisation on the East Alligator River. Scale, 1:50,000.

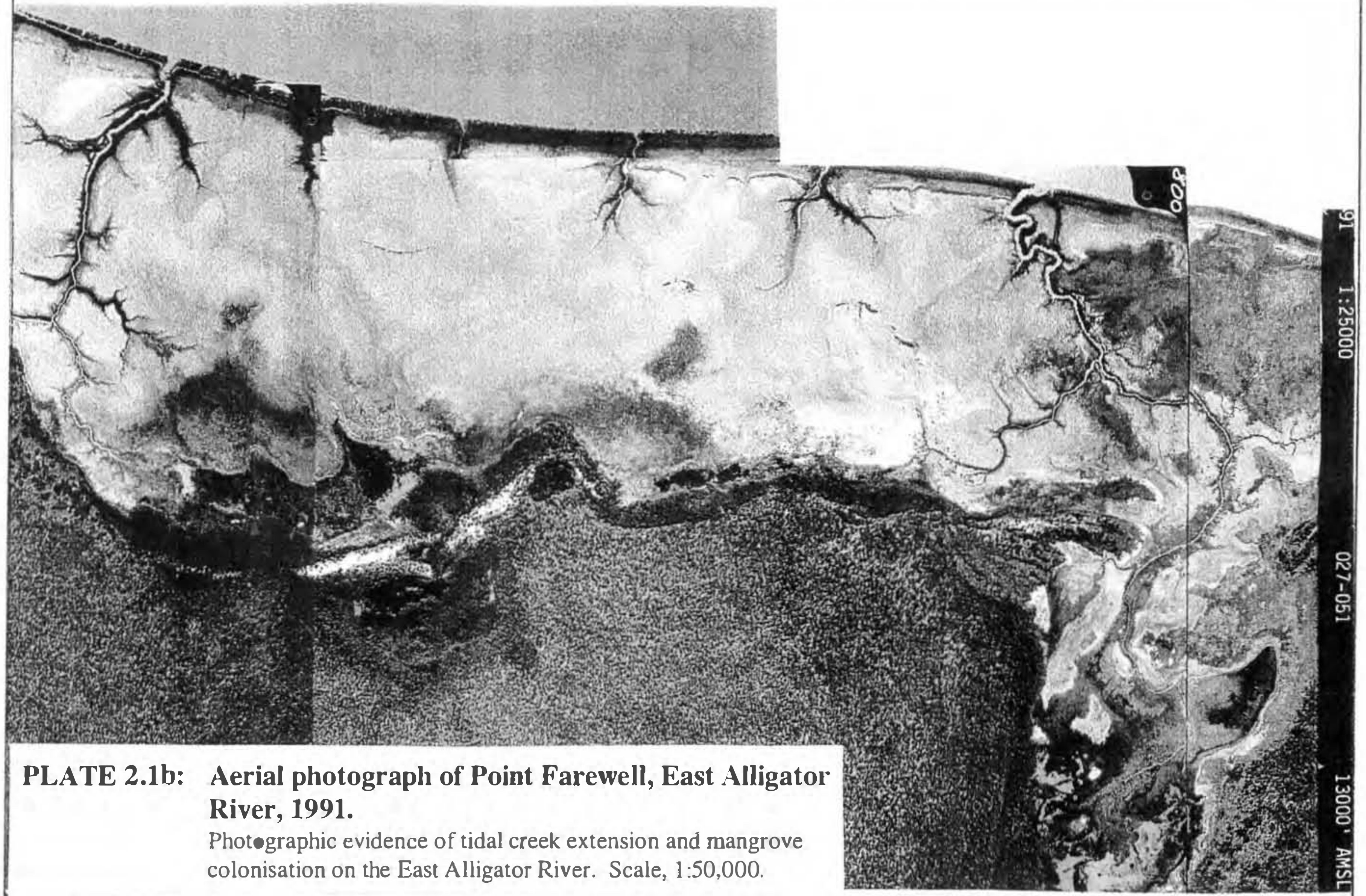


PLATE 2.1b: Aerial photograph of Point Farewell, East Alligator River, 1991.

Photographic evidence of tidal creek extension and mangrove colonisation on the East Alligator River. Scale, 1:50,000.

Munmarlary was selected as a site for the tidal processes operating on the sinuous segments of the river. Examination of aerial photographs for the years 1950 to 1991 revealed evidence of extensive growth of tidal creeks and mangrove encroachment within the confines of a palaeochannel swamp on the western flank of the river (Plate 2.2). Alternate to this trend, on the eastern side there was little evidence of tidal-creek extension (Plate 2.2). Increased mangrove colonisation along already existing creek lines is evidence of an increased saltwater influence. Accessibility to the creek extensions evident within the palaeochannel formation west of the river was limited and unpractical given the time restraints of the fieldwork. Field mapping of the present site morphology was conducted upon the tidal creek to the east of the river. Aerial photographs taken in 1950 and 1991 indicate the creek has remained stable, although mangroves have colonised it since 1950.

2.3.3 Kapalga

Kapalga is located on the cuspate bends of the South Alligator River, approximately 40 km upstream from the river mouth (Figure 2.1). Flood tidal flow is approximately equal to the seasonal freshwater flood discharge within the cuspate segment of the river (Chappell and Woodroffe, 1985). Kapalga was selected as a site for the hydrological processes dominating the mechanism of saltwater intrusion on the cuspate section of the river. Examination of aerial photographs for the years 1950 to 1991 indicate that extensive changes have occurred within the region (Plate 2.3). Analysis of the aerial photographs using a stereoscope indicated the extension of one main tidal creek network into a freshwater swamp, and also indicated evidence of Melaleuca dieback. The Kapalga site was the most accessible of the three field sites and subsequently was revisited over a number of days and the area was extensively mapped.

2.3.4 Potential Sites for Future Research

Field maps were not constructed for a site selected from the fluvial segment of the river due to time restraints. However, broad changes on the South and East Alligator Rivers in recent years are evident from preliminary examination of aerial photographs. The fluvial segment of the South and East Alligator Rivers were characterised by areas of both mangrove encroachment and tidal creek extension. The processes by which saltwater influence extends into the fluvial region may reflect the dominance of the floodwaters in this section of the tidal rivers. Given that there was evidence of saltwater intrusion within the upper reaches of the South and East Alligator Rivers, future research on the trends should include detailed mapping of the morphological characteristics of a changing fluvial environment.

PLATE 2.2a: Aerial photograph of Munmarlary, South Alligator River, 1950.

Photographic evidence of tidal creek extension and mangrove colonisation on the South Alligator River. Scale, 1:25,000.

PLATE 2.2b: Aerial photograph of Munmarlary, South Alligator River, 1991.
Photographic evidence of tidal creek extension and mangrove colonisation on the South Alligator River. Scale, 1:25,000.

PLATE 2.3a: Aerial photograph of Kapalga, South Alligator River, 1950.

Photographic evidence of tidal creek extension and mangrove colonisation on the South Alligator River. Scale, 1:25,000.

PLATE 2.3b: Aerial photograph of Kapalga, South Alligator River, 1991.

Photographic evidence of tidal creek extension and mangrove colonisation on the South Alligator River. Scale, 1:25,000.

The floodplain of the Magela Creek is located within the floodplain of the East Alligator River, some 15 km downstream of Ranger Uranium Mine (Wasson, 1992). The Magela Creek catchment has been subject to considerable research (Finlayson *et al.*, 1989; Finlayson and Woodroffe, 1995; Wasson, 1992). The floodplain has been identified within the literature as a site vulnerable to the long-term effects of climate change and was selected as a specific locality for assessment within the 1995 vulnerability assessment of predicted climate change and sea level rise (Bayliss *et al.*, 1995). The floodplain was viewed as susceptible to the effects of accelerated natural processes resultant from climate change on the tailings dam and other mine features (Wasson, 1992). The Magela Creek floodplain was also delineated as an area at risk to saltwater intrusion in response to sea level rise, shoreline retreat or change in the fluvial regime of the East Alligator River (Bayliss *et al.*, 1995).

The Magela catchment is already exhibiting evidence of environmental change. This change is evident from aerial photographs which indicate the extension of tidal creeks and mangrove colonisation of creeks in the area from 1975 to 1991 (Plate 2.4). The extensive research on the Magela catchment documented to date, in addition to its political significance establishes the area as a suitable site for baseline monitoring. Future research should incorporate a detailed account of the rates and trends of saltwater intrusion within the Magela Creek floodplain.

2.4 FIELD SURVEY TECHNIQUES

Detailed field mapping and general morphological descriptions were conducted at the three selected sites from different geomorphological settings exhibiting change; Point Farewell, Munmarlary and Kapalga. All field work was undertaken during the month of August in the Dry season, over a total period of eight days.

2.4.1 Differential Global Positioning System

The main morphological components of the field sites were mapped using an ASHTECH differential Global Positioning System (dGPS), as an accurate record of the boundaries of present site morphology, and an indication of the trends of saltwater intrusion currently occurring. The base station unit of the dGPS was a dual frequency z-12 receiver. It was necessary to set the receiver over a point of known location, such as a geodetic point or bench mark (Plate 2.5). The location of the known geodetic sites used as base stations for sites Kapalga and Munmarlary is listed in Table 2.2.

PLATE 2.4 a: Aerial photograph of the Magela Creek joining the East Alligator River, 1975.

Photographic evidence of increased mangrove colonisation of creek lines in the Magela catchment. Scale 1:25,000.

PLATE 2.4 b: Aerial photograph of the Magela Creek joining the East Alligator River, 1991.
Photographic evidence of increased mangrove colonisation of creek lines in the Magela catchment. Scale 1:25,000.

TABLE 2.2 : Location of Geodetic Sites

Name	Latitude	Longitude	Zone	Easting	Northing	Height m
Kapalga NTS 018	-12 42 33.2344	132 26 3.3034	53	221360.635	8593640.798	110.600
Munmarlary U 689	-12 28 47.5668	132 29 19.8213	53	227049.642	8619083.356	12.600

Coordinate Datum: AGD84

Plate 2.5: Dual frequency z-12 receiver

Base station equipment at geodetic site, Kapalga (NTS 018)

It was not possible to position the base station over the station mark at the Kapalga geodetic site (NTS 018), as the beacon would interfere with the signal. As an alternative the z-12 receiver was positioned over one of the marker spikes. Since the distance between the spike and the station mark was known, it was possible to determine the relative height of the spike. There was no known reference bench mark or geodetic site at Point Farewell. Therefore, the dGPS base station was positioned over an unknown datum. The base station required a field reference site and as there were no significant rocks or permanent features available, the receiver was set up over a randomly selected site. This location was marked with a star picket.

Features of each site were mapped using the Reliance rover of the dGPS. The rover had a portable Marine IV antenna which could be mounted on vehicle, boat, pole, or carried on back (Plate 2.6). The outskirts of the intruding creek at the Kapalga site were mapped using the rover receiver mounted on a boat (Plate 2.7). Tidal creeks were mapped during a spring high tide of seven metres. This enabled travelling as far upstream as possible without getting stranded as the tide went out. 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 (Plate 2.8), single mangroves, areas of dead mangroves, and areas of mangrove seedlings. Five second logging intervals were set for line and area features, and 20 seconds for point features.

Plate 2.6: Reliance Rover Receiver
The Marine IV antenna of the Reliance rover receiver mounted on quad bike, operated by a hand-held control.

Plate 2.7: Mapping the outskirts of a tidal creek on boat, Kapalga
Outskirts of tidal creeks mapped by the Reliance rover receiver mounted on boat at spring high tide (seven metres).

Field observations and photos 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. Soil samples were taken from Kapalga and Point Farewell for descriptive laboratory analysis. Location of soil samples were mapped using the dGPS. An example of the field program is outlined in Appendix 2.

2.4.2 Data Processing

The dGPS data logged in the field was down-loaded daily from both the base station and the rover receiver to the Reliance software package. The down-loaded field data was then processed using the Reliance software, which generated the corrected data to a graphical format. Once processed, the data was exported to text files (txt.file) which may be viewed in Word or a spreadsheet. Logged information included recordings of latitude and longitude values, elevations, and measurements of accuracy. The processed data was exported into generate files (gen.files) and manipulated in Arc Info and Arc Edit to generate maps of each field site.

Plate 2.8: Mapping tidal creeks on quad bike, Kapalga

Tidal creeks mapped by the Reliance rover receiver mounted on quad bike. Tidal creeks were mapped at low tide.

2.5 ANALYSIS

2.5.1 Network Properties

Geometric and topologic properties of the Wildman, West, South and East Alligator River networks, were determined as measures of the rate and modes of tidal creek and mangrove growth over the years 1950 to 1991. Network magnitude is a topologic variable corresponding to the number of exterior links of first order channels (Shreve, 1967), and was used as a measure of network size. Mangrove area was calculated from the maps constructed for each year, 1950, 1975, 1984 and 1991, as a measure of the rate of mangrove encroachment. Network magnitude and mangrove area were calculated for each river system and for the field sites Kapalga, Munmarlary and Point Farewell that were mapped in detail.

Stream order is a topologic variable which expresses the hierarchical relationship between creek segments. The tidal creeks of the field sites Kapalga, Munmarlary and Point Farewell were ordered using the Strahler (1964) system, which defines a creek with no tributaries as a first order segment. A second order segment is a creek which is formed by the joining of two first order segments and a third order segment is joined by two second order segments and so on. Creek lengths were measured from the detailed maps constructed for each field site, Kapalga, Munmarlary and Point Farewell for the years 1950 to 1991 using an opisometer. Creek lengths were measured only for the field sites, given they were mapped at a large scale, 1: 25,000, and would therefore be measured with greater accuracy.

2.5.2 Laboratory

Soil electrical conductivity was determined for all soil samples collected in the field. The electrical conductivity of a soil : water extract is used to estimate soluble salt concentration in soils (McArthur, 1991). Electrical conductivity (range 0.51 - 41.30 mS/cm; mean 8.86 mS/cm) were measured on 1 : 5 soil water suspensions (Rayment and Higginson, 1992).

CHAPTER 3: RESULTS

3.1 ORGANISATION OF RESULTS

Changes in the spatial characteristics and distribution of tidal creeks and mangroves in the Alligator Rivers Region were reconstructed from aerial photography at a working scale of 1:100,000, and are presented in a series of map compositions at 1:250,000. The trends of network growth and mangrove expansion are depicted in graphical format for each river system and related to the spatial distribution patterns. Information collated from aerial surveys, field observations and ground mapping were compiled to demonstrate recent changes at specific sites at two scales, 1:25,000 and less than 1:20,000, and present morphological evidence of the localised processes of saltwater intrusion.

3.2 GROSS CHANGES IN THE DISTRIBUTION OF TIDAL CREEKS AND MANGROVES IN KAKADU NATIONAL PARK BETWEEN 1950 AND 1991

The coastal fringe of Kakadu National Park, of the eastern Alligator Rivers Region, is drained by four main estuarine river systems; the Wildman, West, South and East Alligator Rivers (Figure 1.2). Since the late 1940's-early 1950's these rivers have expanded their tidal influence along extending creek lines and the resultant changes in the saltwater reaches have been coupled with extensive mangrove encroachment.

3.2.1 South Alligator River

The South Alligator River is the largest of the estuarine rivers in the Alligator Rivers Region. From 1950 to 1991, existing tidal creeks of the South Alligator River had developed through a combination of headward extension and tributary growth (Figure 3.1). In 1950, there were small creek tributaries branching from each river segment; the estuarine funnel, sinuous and cuspate meanders, and the fluvial reach (Figure 3.1a). At this time, tributary development was relatively limited in the sinuous, cuspate and upstream segments of the river. The most extensive network of tributaries was within and extending from a large palaeochannel on the eastern flank of the estuarine funnel (Figure 3.1a).

By 1975, the tidal creeks which appeared relatively inactive in 1950 had extended in the middle and lower reaches of the South Alligator River (Figure 3.1a). A number of creeks had successfully invaded the series of palaeochannels flanking the sinuous and meander segment of the river. Small creeks also extended from the main channel in the fluvial reach. Tributary

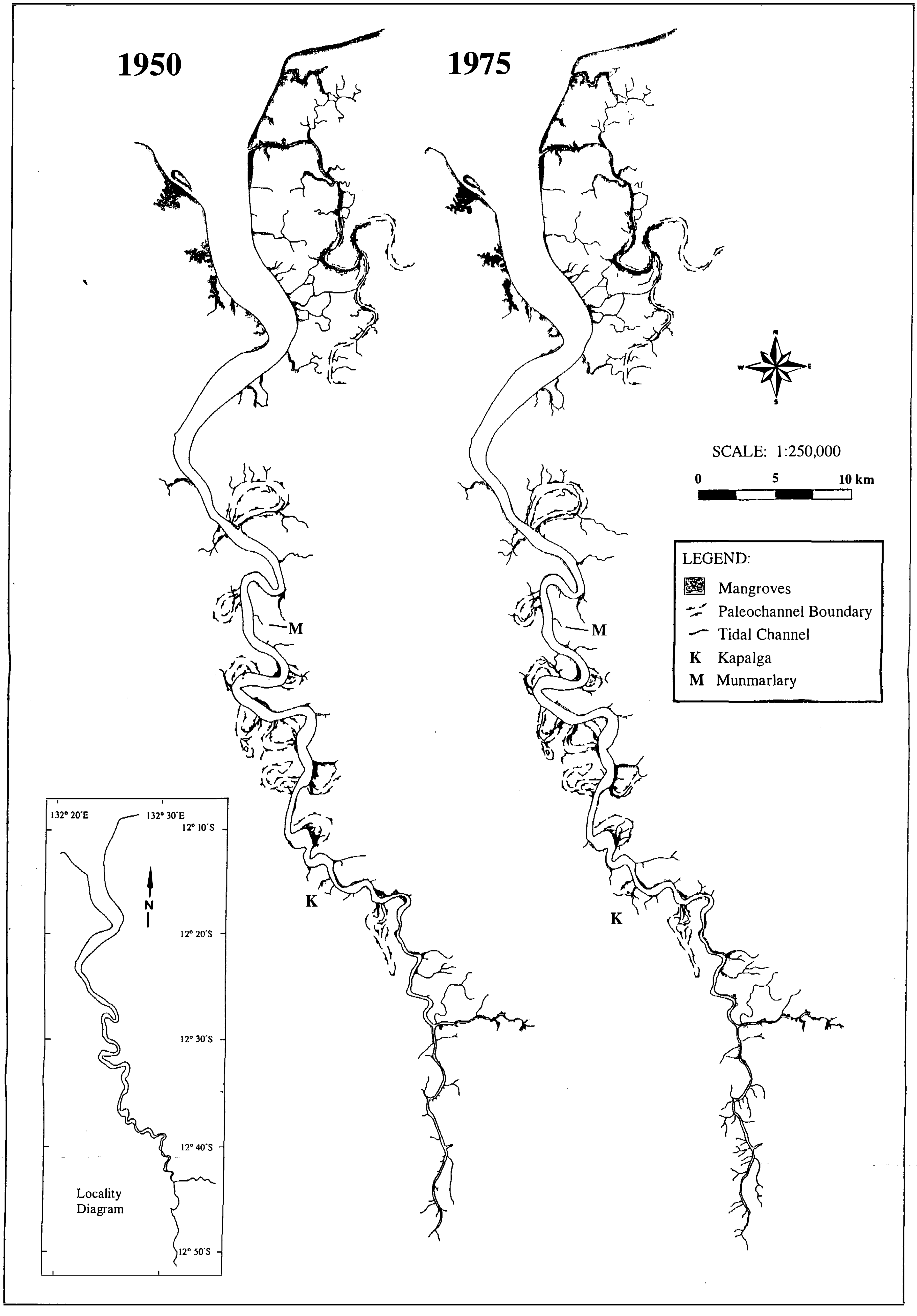


FIGURE 3.1a: Tidal creek extension and the extent of mangrove encroachment on the South Alligator River, 1950 - 1975.

Source: The tidal creeks and mangrove boundaries were mapped from 1950 and 1975 aerial photography. The paleochannel distribution information is correct to 1971, mapped from the Australian 1:250,000 Geological Series map of the Alligator River; published by the Bureau of Mineral Resources, Geology and Geophysics Dept. of National Development and Energy, 1983.

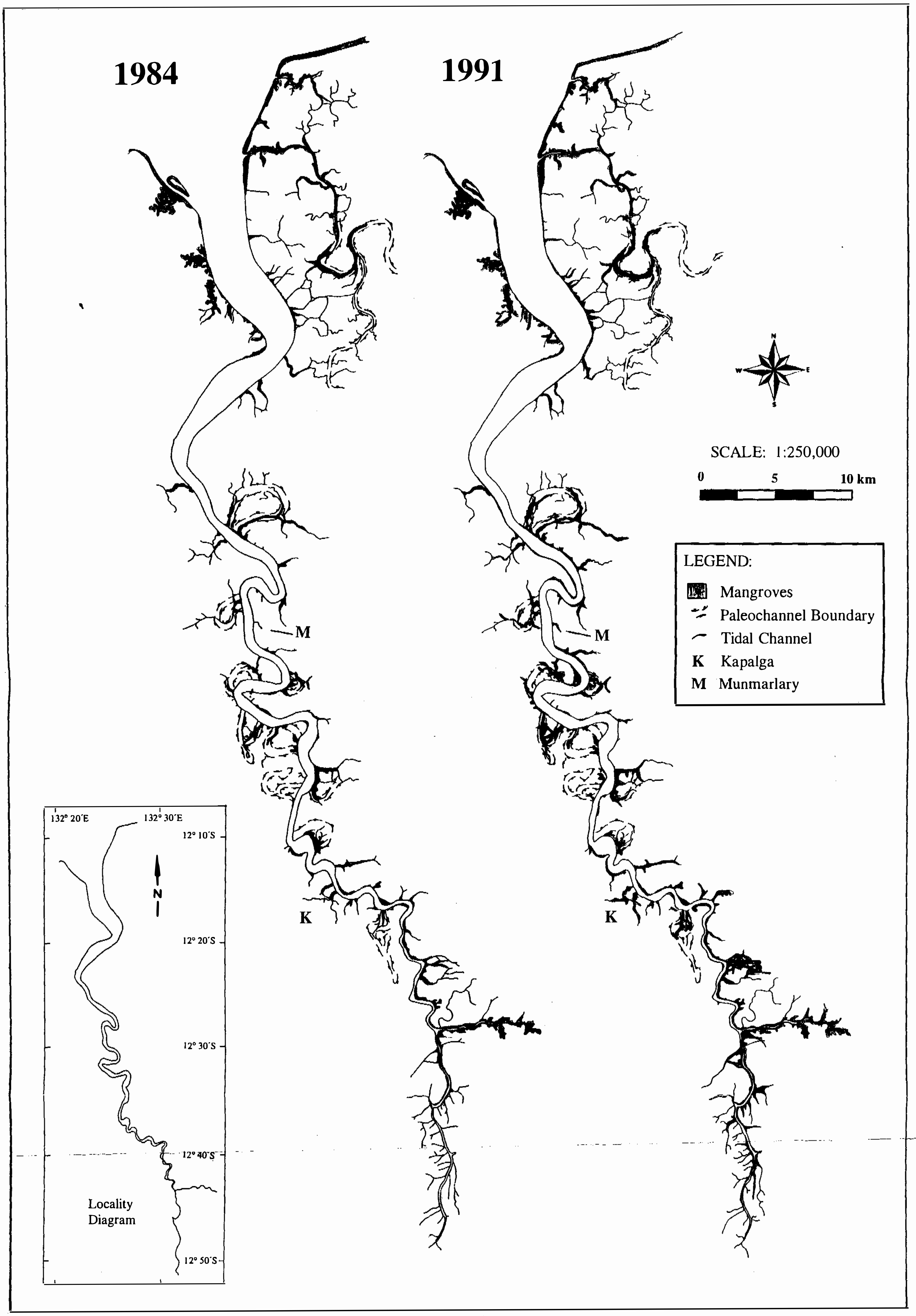


FIGURE 3.1b: Tidal creek extension and the extent of mangrove encroachment on the South Alligator River, 1984 - 1991.

Source: The tidal creeks and mangrove boundaries were mapped from 1984 and 1991 aerial photography. The paleochannel distribution information is correct to 1971, mapped from the Australian 1:250,000 Geological Series map of the Alligator River; published by the Bureau of Mineral Resources, Geology and Geophysics Dept. of National Development and Energy, 1983.

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 palaeo boundaries along the meanders of the South Alligator River, whilst they remained fairly limited elsewhere (Figure 3.1b). The importance of small topographic variations in tidal creek development is evident from this trend of growth.

Expansion of the tidal influence along extending creek lines of the South Alligator River is reflected by the spatial changes in the shoreline distribution of mangroves. Since the late 1940's-early 1950's, mangroves extended along the main tributaries of the South Alligator River as they became more tidally active (Figure 3.1). In 1950, mangroves had extensively colonised the shoreline and main channels of the estuarine funnel. At this time mangroves encroached the main tributary lines in the sinuous and cuspate segments of the river only in patches and few mangroves colonised the upstream segment of the river (Figure 3.1a). By 1991 mangroves had extended to the upper reaches of the South Alligator River, which is dominated by fresh floodwaters. Mangroves had also encroached the higher order channels from the sinuous and cuspate meanders and along the lower creek lines within the palaeochannels (Figure 3.1b).

3.2.2 East Alligator River

The East Alligator River lies approximately 25 km north-east of the South Alligator River within the Kakadu National Park boundary (Figure 1.2). From 1950 to 1991, the branching tributaries from the East Alligator River extended in a similar trend to that described for the South Alligator River. Tidal creek extension occurred through a combination of headward extension of the main channels and the growth of tributaries (Figure 3.2).

In 1950, two main creeks dominated the sinuous and cuspate segments of the East Alligator River (Figure 3.2a). The creek extending from the sinuous segment had not extended further than two kilometres south of the river channel, with few headwater tributaries. Similarly, the main tributary of the cuspate segment (the Magela Creek), had not extended south further than five kilometres. Small creeks branched from each river segment, although significant tributary development was limited on the East Alligator River at this time (Figure 3.2a).

By 1975, both of the main channels in the meander river segment had bifurcated into more distinctly defined tributary networks (Figure 3.2a). The tidal creeks in the upstream segment of the East Alligator River extended predominantly along the paths of the palaeochannels (Plate

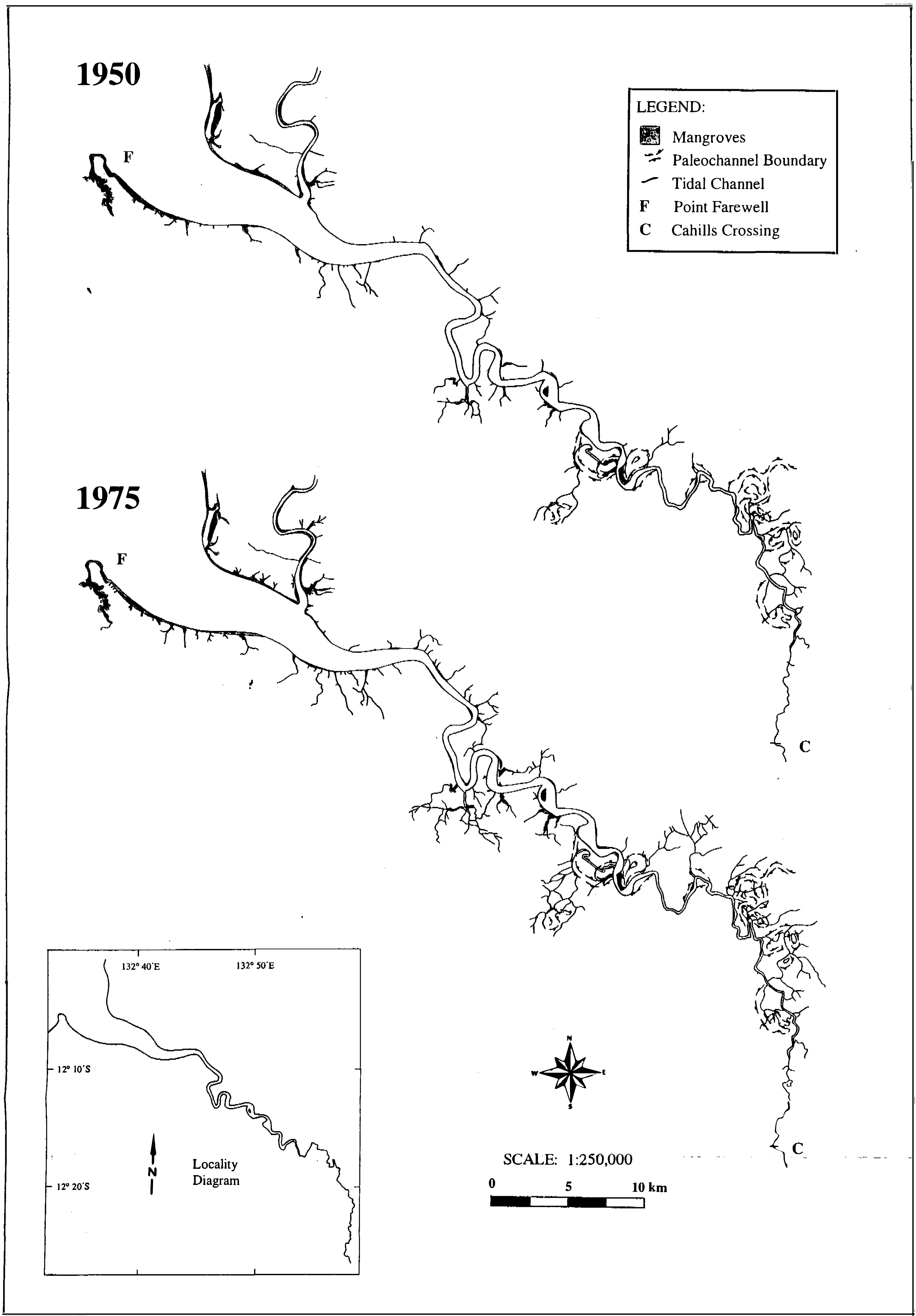


FIGURE 3.2a: Tidal creek extension and the extent of mangrove encroachment on the East Alligator River, 1950 - 1975.

Source: The tidal creeks and mangrove boundaries were mapped from 1950 and 1975 aerial photography. The paleochannel distribution information is correct to 1971, mapped from the Australian 1:250,000 Geological Series map of the Alligator River; published by the Bureau of Mineral Resources, Geology and Geophysics Dept. of National Development and Energy, 1983.

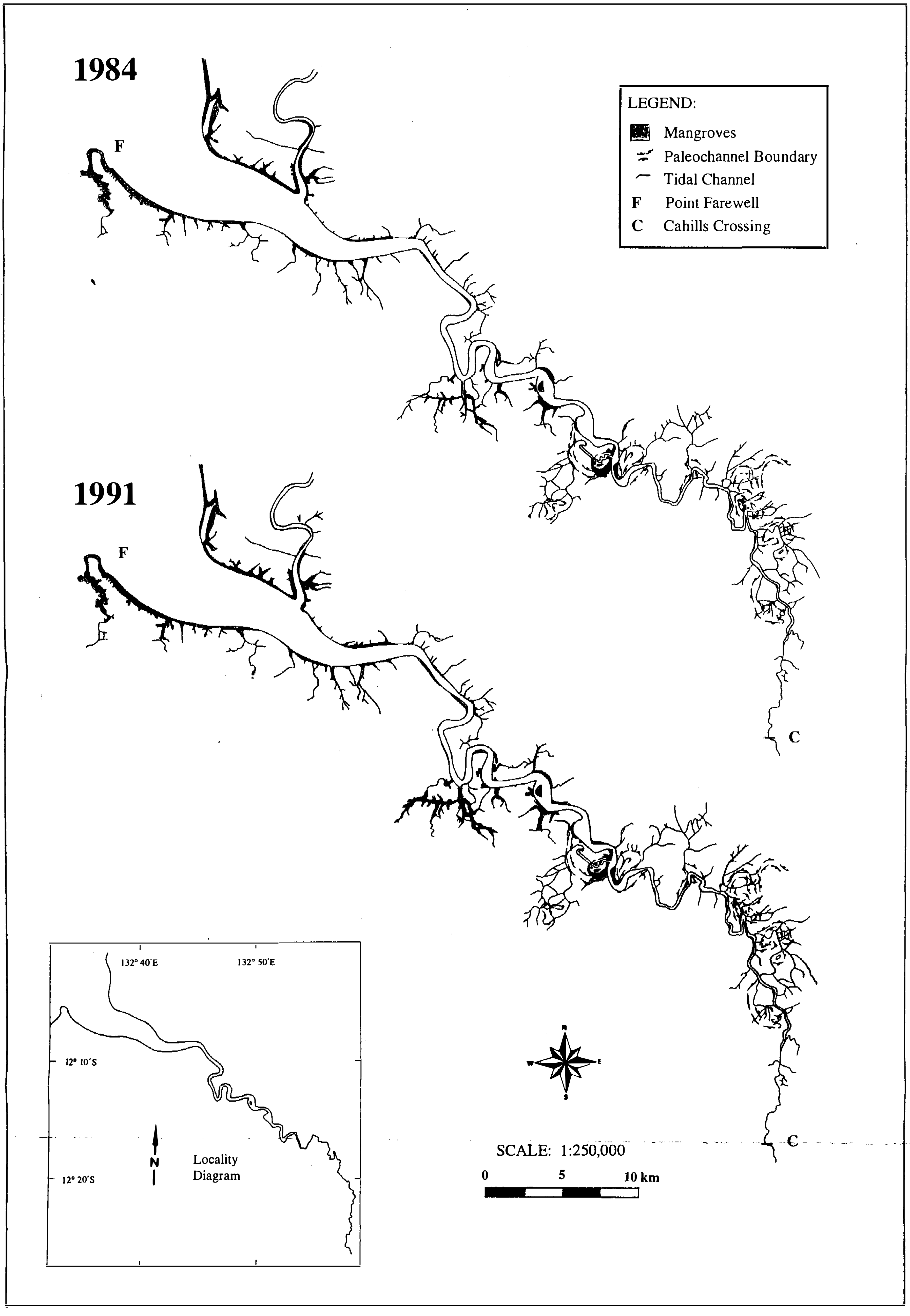


FIGURE 3.2b : Tidal creek extension and the extent of mangrove encroachment on the East Alligator River, 1984 - 1991.

Source: The tidal creeks and mangrove boundaries were mapped from 1984 and 1991 aerial photography. The paleochannel distribution information is correct to 1971, mapped from the Australian 1:250,000 Geological Series map of the Alligator River; published by the Bureau of Mineral Resources, Geology and Geophysics Dept. of National Development and Energy, 1983.

3.1). Tidal creeks also extended through mainly headward growth within the confines of the palaeochannels and with few branching tributaries (Figure 3.2a). Whilst the most active creeks were those invading the lower topography of the palaeochannels, the single creeks of the estuarine funnel had also extended since 1950.

Tributary growth continued in the upstream river segment within the palaeomeanders from 1975 to 1991. Some of the small tributaries flanking the estuarine funnel extended south as far as two and a half kilometres (Figure 3.2b). Little further extension occurred in either of the two main tidal creeks of the meander segment of the river.

Since the late 1940's mangroves accompanied the expansion of creek lines on the East Alligator River as they became more tidally active (Figure 3.2). In 1950 mangroves flanked the shoreline boundary of the estuary mouth, and sparsely colonised shoals and point bars of the cuspate meanders (Figure 3.2a). At this stage mangroves were generally limited to the main river channel in the meander and upstream segments of the river, although they had begun to encroach the Magela Creek (Figure 3.2a).

Plate 3.1: Palaeomeander Cutoff on the East Alligator River
Scattered mangroves encroaching the palaeochannel swamp in the upstream segment of the East Alligator River (The "Hook").

By 1984, mangroves had rapidly encroached the main tidal channel on the southern flank of the sinuous segment of the river, which had not been encroached in 1975 (Figure 3.2b). The period of mangrove encroachment on the tidal channel corresponds to a lapse in the rate of tidal creek extension.

By 1991, the spatial distribution of mangroves on the East Alligator River was no longer confined to the main river channel. Mangroves had colonised the shoreline of the funnel more densely, and had encroached some of the channels which extended from the river mouth since 1975 (Figure 3.2b). The tidal channel and branching first order creeks of the sinuous river segment were densely colonised by 1991. The point bars and shoal forms of the both the sinuous and cuspate meanders were flanked with mangroves, and mangroves encroached the palaeo meander cutoff where the Magela Creek joins the East Alligator River (Figure 3.2b).

3.2.3 Wildman and West Alligator River

The Wildman and West Alligator Rivers are the nearest western neighbours of the South Alligator River, and lie within the western flank of Kakadu National Park (Figure 1.2). Since the late 1940's-early 1950's, tidal creeks of both the Wildman and the West Alligator River have developed, although not at the rate or to the extent as that observed on both the South and East Alligator Rivers. Both rivers exhibited marked changes in the shoreline distribution of mangroves, suggesting expansion of the tidal reach such as that observed coupling the dramatic creek extensions on the South and East Alligator Rivers (Figures 3.3 and 3.4).

The trends of mangrove colonisation on the Wildman and West Alligator Rivers since 1950 are similar to those observed for the South and East Alligator Rivers. Mangrove encroachment has occurred along the main tributaries of both the Wildman and West Alligator Rivers, and along smaller creek lines as they became more tidally active (Figures 3.3 and 3.4). Mangroves densely flank the shoreline of both river systems, with colonisation becoming more sparse in the upper reaches of the rivers. The fluvial segments of both rivers have a limited distribution of mangroves, although from 1950 to 1991 mangroves had extended approximately four kilometres upstream on the West Alligator River (Figure 3.3).

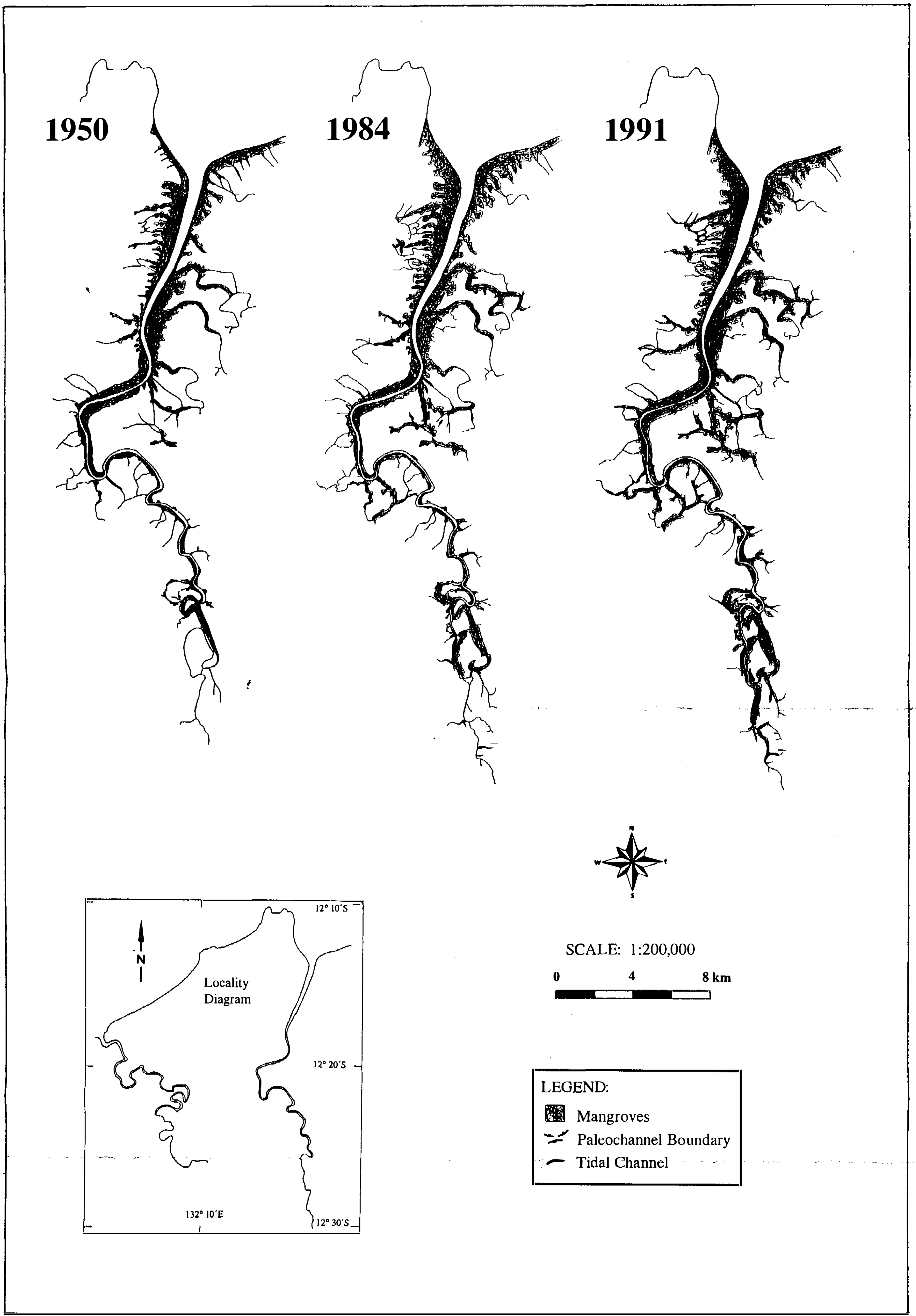


FIGURE 3.3 : Tidal creek extension and the extent of mangrove encroachment on the West Alligator River, 1950 - 1991.

Source: The tidal creeks and mangrove boundaries were mapped from 1950, 1984 and 1991 aerial photography. The paleochannel distribution information is correct to 1971, mapped from the Australian 1:250,000 Geological Series map of the Alligator River; published by the Bureau of Mineral Resources, Geology and Geophysics Dept. of National Development and Energy, 1983.

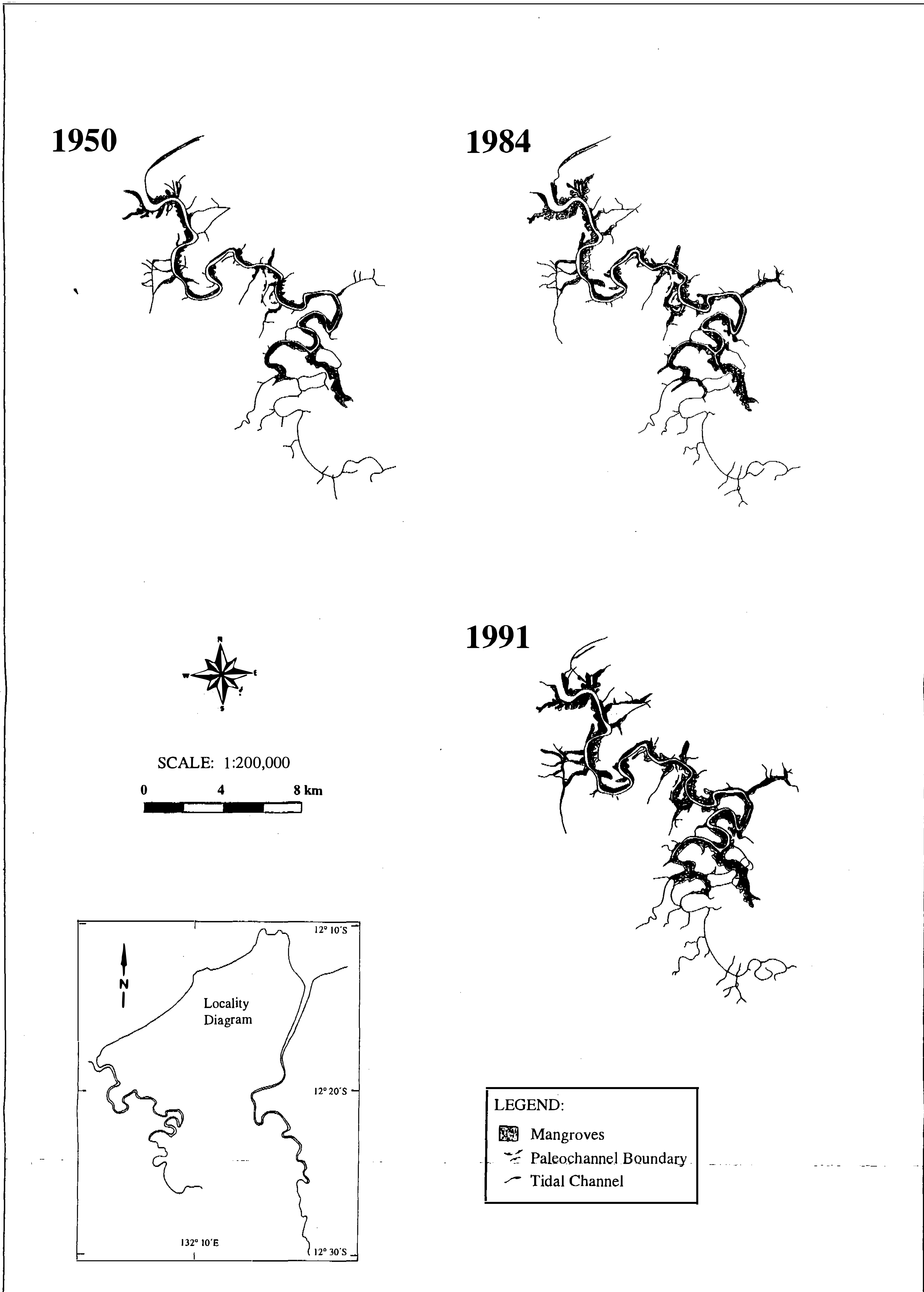


FIGURE 3.4 : Tidal creek extension and the extent of mangrove encroachment on the Wildman River, 1950 - 1991.

Source: The tidal creeks and mangrove boundaries were mapped from 1950, 1984 and 1991 aerial photography. The paleochannel distribution information is correct to 1971, mapped from the Australian 1:250,000 Geological Series map of the Alligator River; published by the Bureau of Mineral Resources, Geology and Geophysics Dept. of National Development and Energy, 1983.

3.2.4 Tidal Creek Growth Trends

Using network magnitude as a measure of network size, the South Alligator River has experienced an exponential rate of growth, with a significant increase in growth rate post 1975, after which time a period of rapid tidal creek extension took place (Figure 3.5). Similarly, the Wildman river experienced an exponential rate of growth, with a significant increase in growth rate post 1984, although data for 1974 was not available (Figure 3.5). In contrast to this, the growth rates of the East and West Alligator Rivers show a linear trend, with rates of growth remaining relatively consistent from 1950 to 1991 (Figure 3.5).

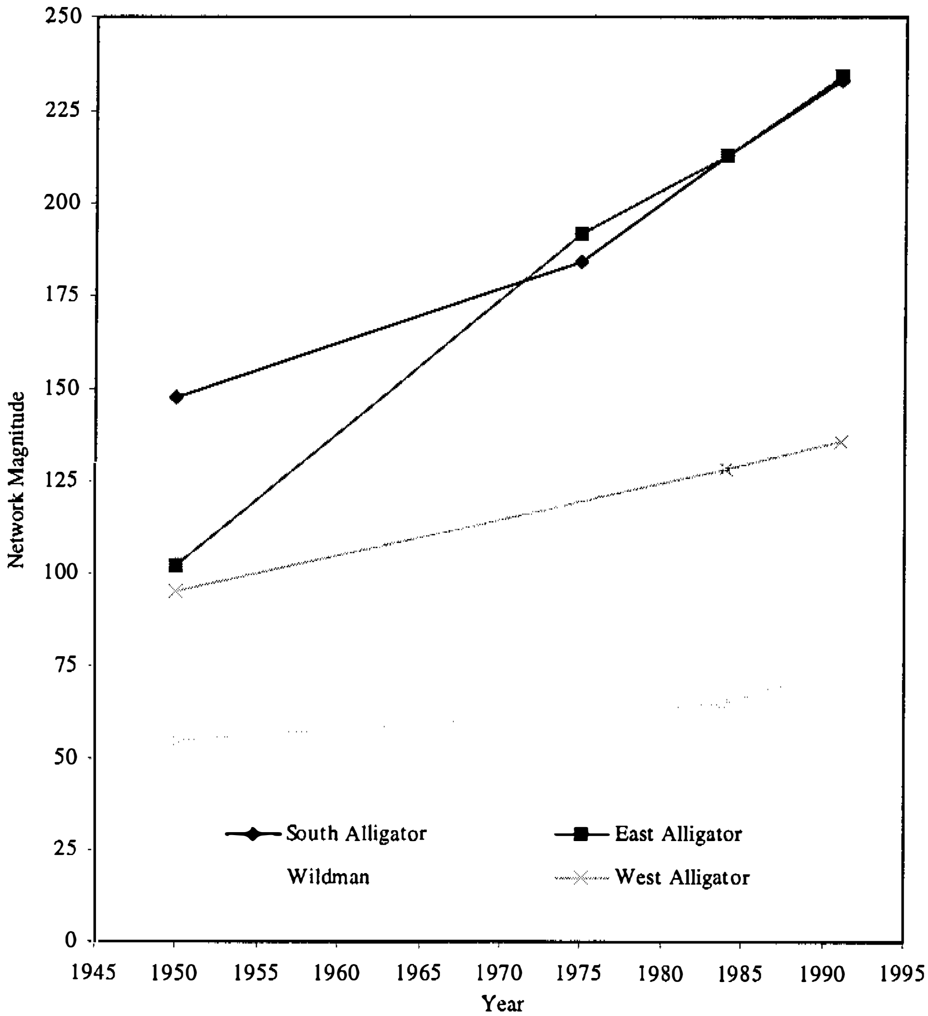


FIGURE 3.5: Network Magnitude over Time

The rates of tributary growth from 1950 to 1991 varied between the Wildman and the South Alligator River, although the trends of growth were both exponential (Figure 3.5). There were insufficient data points of network magnitude over time to establish an accurate exponential regression line for the South Alligator and Wildman River growth trends. However, it is evident from Figure 3.5 that the rates of growth changed over time. From 1984 to 1991, the South Alligator River expanded more rapidly than the Wildman over the same time period, with an increase in network magnitude of 20 as opposed to 10 (Figure 3.5). The South Alligator River also attained a significantly higher magnitude (233) as opposed to the Wildman (75), although this may be attributed to the size difference between the river systems and main tributaries.

Although both rivers experienced a linear growth rate, the rates of growth between 1950 and 1991 varied greatly between the East Alligator River and the West Alligator River. The network magnitude of the East Alligator River increased by 132 from 1950 to 1991, whilst over the same time period, the West Alligator River had increased by 41 (Figure 3.5).

Despite an overall exponential rate of tidal creek growth on the South Alligator River, the characteristics of network growth varied with the morphological changes in the river channel (Figure 3.6a). Little growth had occurred in the estuarine funnel and sinuous segments of the river until 1975, after which tidal creeks began extending in a linear or arrested pattern, with a slow rate of change. In the upstream reaches of the river, including the cuspate meanders and fluvial segment respectively, network growth occurred in a linear and weakly exponential trend.

The characteristics of network growth varied with the morphological differences in the river channel of the East Alligator River, despite an overall linear progression of network development from 1950 to 1991 (Figure 3.6b). In contrast to the trends observed for the South Alligator River, linear growth was observed for both the funnel and fluvial segments of the East Alligator River, whilst arrested tributary development occurred within the meanders.

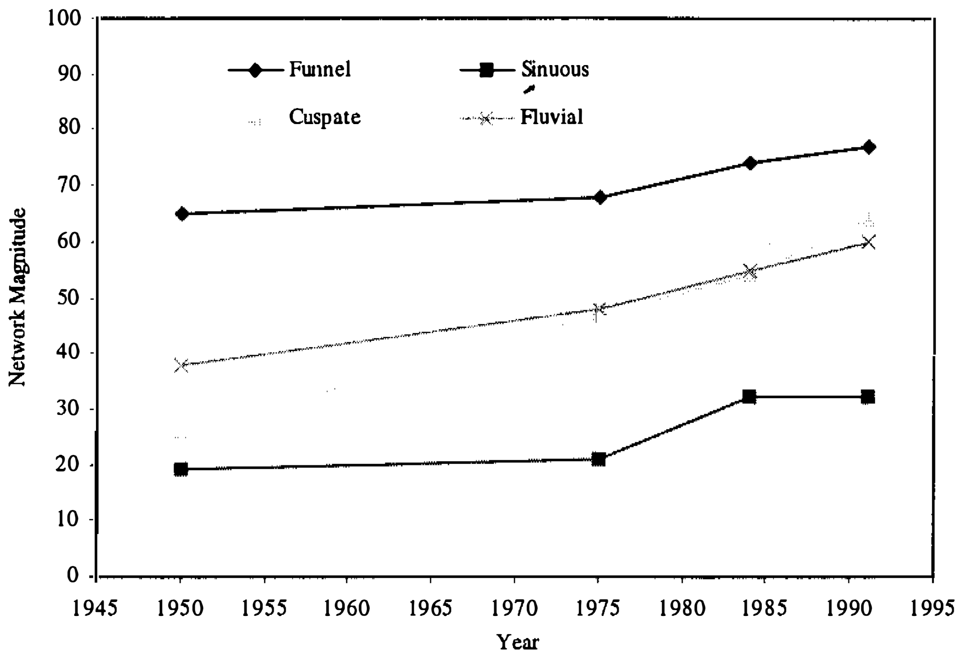


FIGURE 3.6a : Changes in Network Magnitude over Time, at the Different Stream Segments identified by Chappell, (1988) - South Alligator River

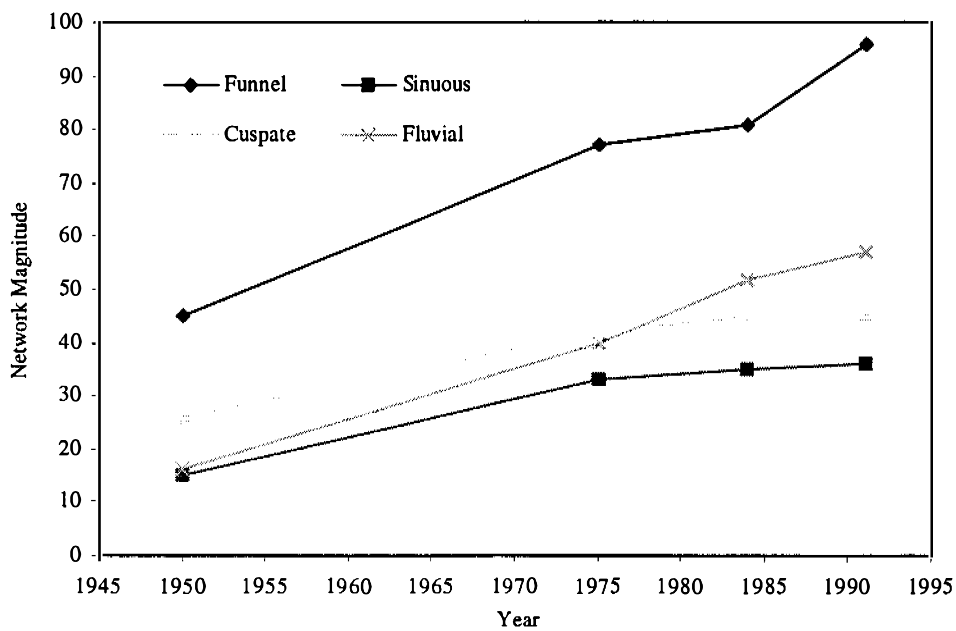


FIGURE 3.6b : Changes in Network Magnitude over Time, at the Different Stream Segments identified by Chappell, (1988) - East Alligator River

3.2.5 Mangrove Growth Trends

The Wildman, West, South and East Alligator Rivers each experienced an exponential rate of mangrove growth from 1950 to 1991, although the rates of change between the rivers were quite varied (Figure 3.7). Mangrove expansion had occurred most rapidly on the West and South Alligator Rivers, with the most significant growth rates occurring post 1975 (Figure 3.7). From 1984 to 1991, total mangrove area on the South and West Alligator Rivers increased by 13 and 9 km^2 respectively. Over the same time period, mangrove growth on the Wildman and East Alligator Rivers increased by 3 and 4 km^2 respectively.

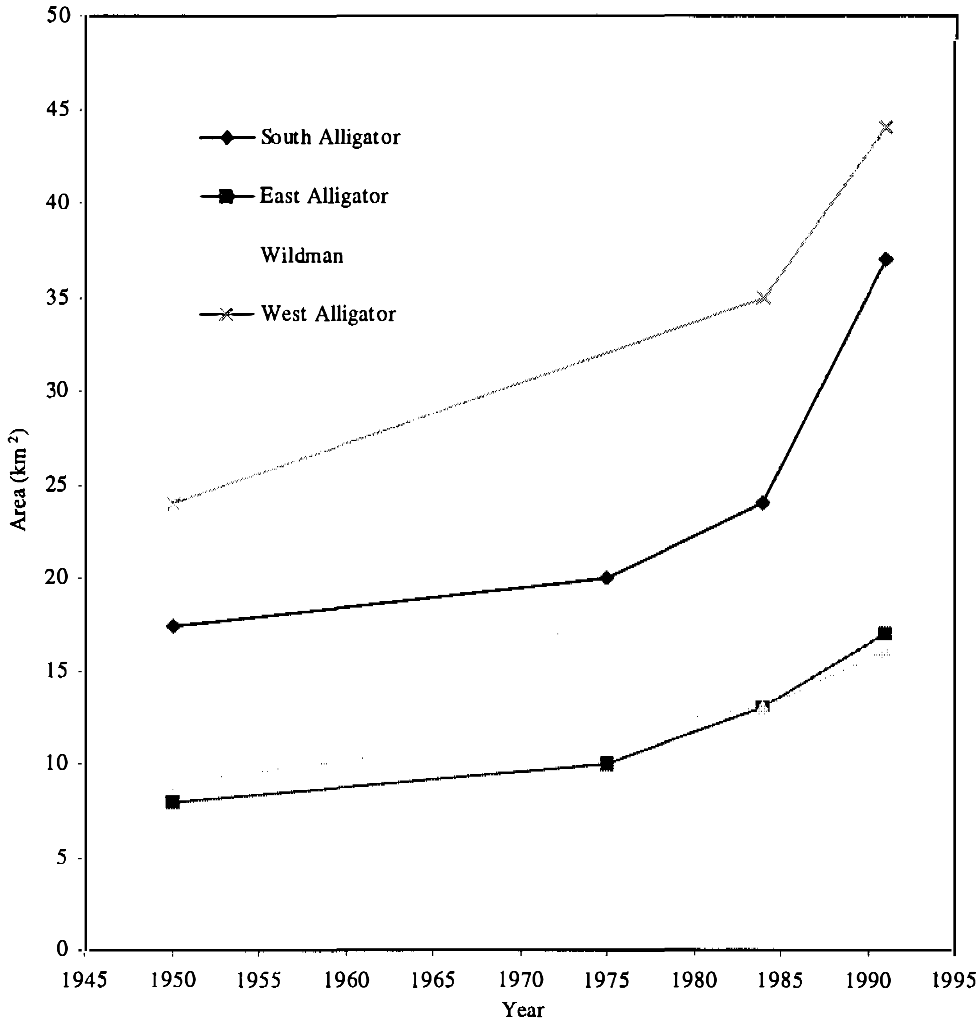


FIGURE 3.7 : Total Mangrove Area over Time

Despite an overall exponential rate of mangrove growth on the four river systems, the trends of mangrove growth varied with the morphological changes in the river channels (Figure 3.8). On the South Alligator River mangrove growth occurred in a weakly exponential trend in the upper reaches of the river, and in the estuarine funnel (Figure 3.8a). Little growth occurred from the meanders of the South Alligator until 1984, after which time both the sinuous and cuspate segments experienced a period of rapid mangrove encroachment .

On the East Alligator River, the trends of mangrove growth from 1950 to 1991 were similar to that observed on the South Alligator. The rate of mangrove growth in the estuarine funnel was weakly exponential, and limited growth occurred from the meander segments until 1984 (Figure 3.8b). However, unlike the weakly exponential trend observed for the South Alligator River, mangrove growth occurred in an arrested trend in the upper fluvial segment of the East Alligator River.

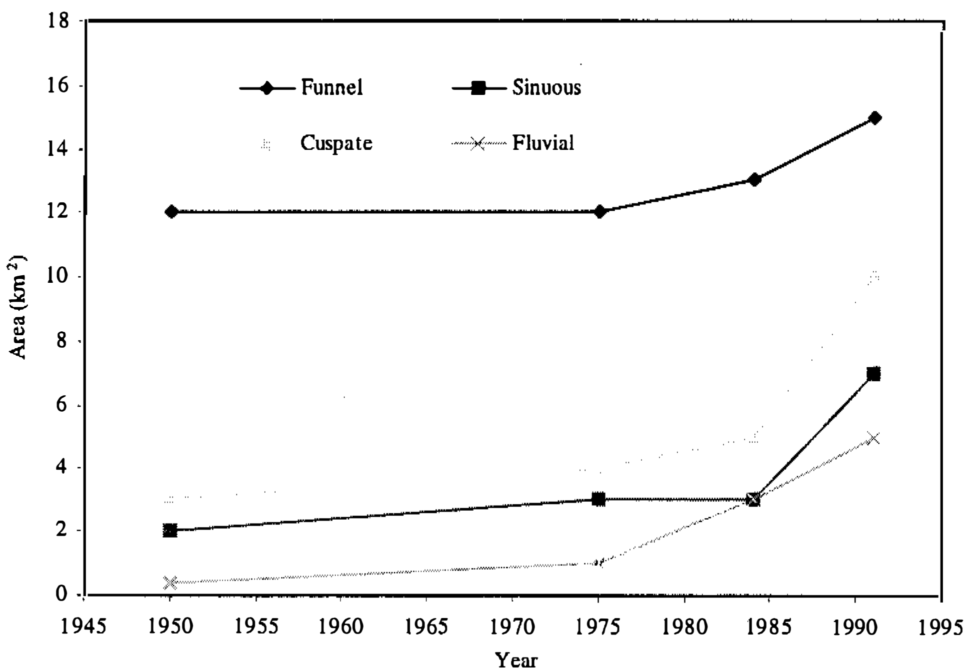


FIGURE 3.8a : Changes in Mangrove Area over Time, at the Different Stream Segments identified by Chappell, (1988) - South Alligator River

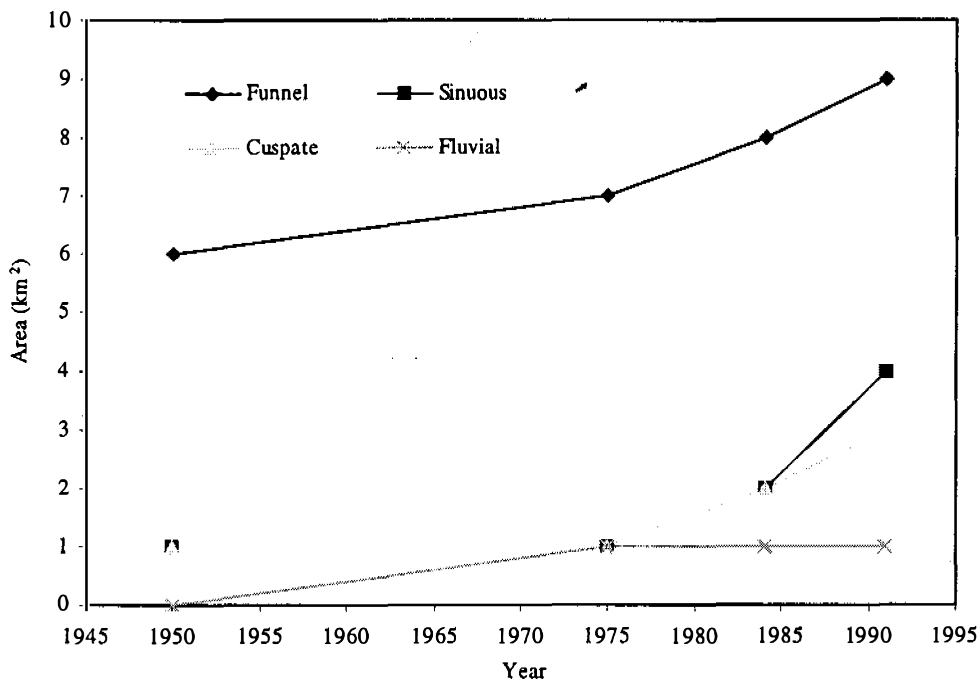


FIGURE 3.8b : Changes in Mangrove Area over Time, at the Different Stream Segments identified by Chappell, (1988) - East Alligator River

3.3 DISTRIBUTION AND MORPHOLOGY OF TIDAL CREEKS AND MANGROVES AT SPECIFIED LOCATIONS

3.3.1 Point Farewell

From 1950 to 1991, small tidal creeks within the vicinity of Point Farewell rapidly extended south of the shoreline through a combination of both headward extension and tributary growth (Figure 3.9). In 1950, the tidal creeks within the region had not extended further than two kilometres inland and significant tributary development was limited (Figure 3.9a). Mangroves flanked the shoreline of the estuarine funnel and had encroached the downstream limits of the main creek lines. By 1975, three of the main channels had experienced marked channel extension, dominantly by means of tributary development. By 1984 the main channels had extended through further headward extension. One of the main creek lines was coupled with mangrove encroachment along its higher order tributaries (Figure 3.9b). By 1991, two main channels had established well defined networks and mangroves had encroached the higher order

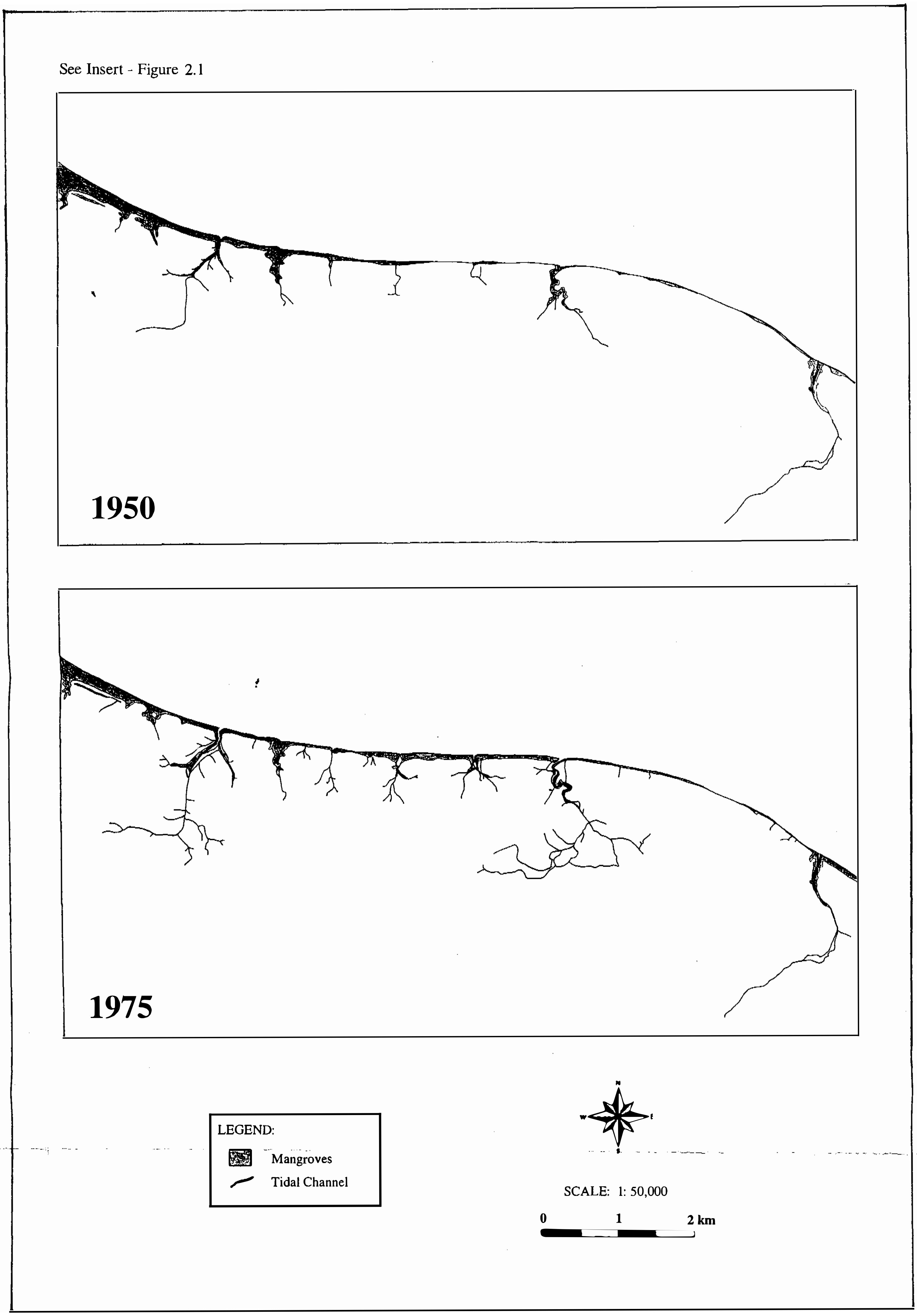


FIGURE 3.9a : Tidal creek and mangrove extension at Point Farewell, East Alligator River, 1950 - 1975.

Source: The tidal creeks and mangrove boundaries were mapped from 1950 and 1975 aerial photography at a working scale of 1: 25,000.

See Insert - Figure 2.1

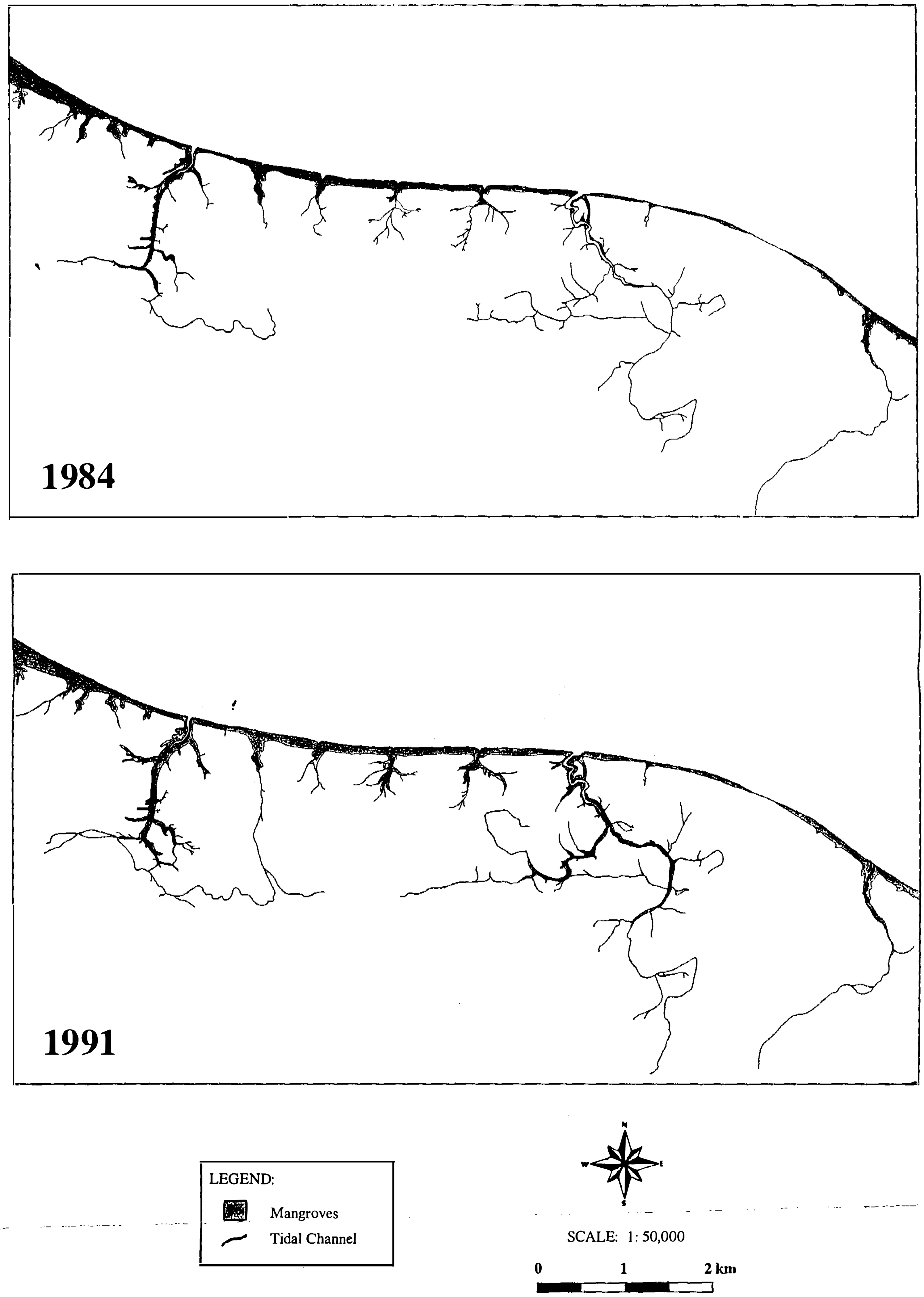


FIGURE 3.9b : Tidal creek and mangrove extension at Point Farewell, East Alligator River, 1984 - 1991.

Source: The tidal creeks and mangrove boundaries were mapped from 1984 and 1991 aerial photography at a working scale of 1: 25,000.

tributaries (Figure 3.9b). Mangrove colonisation also became increasingly dense along both the coastline and main creeks.

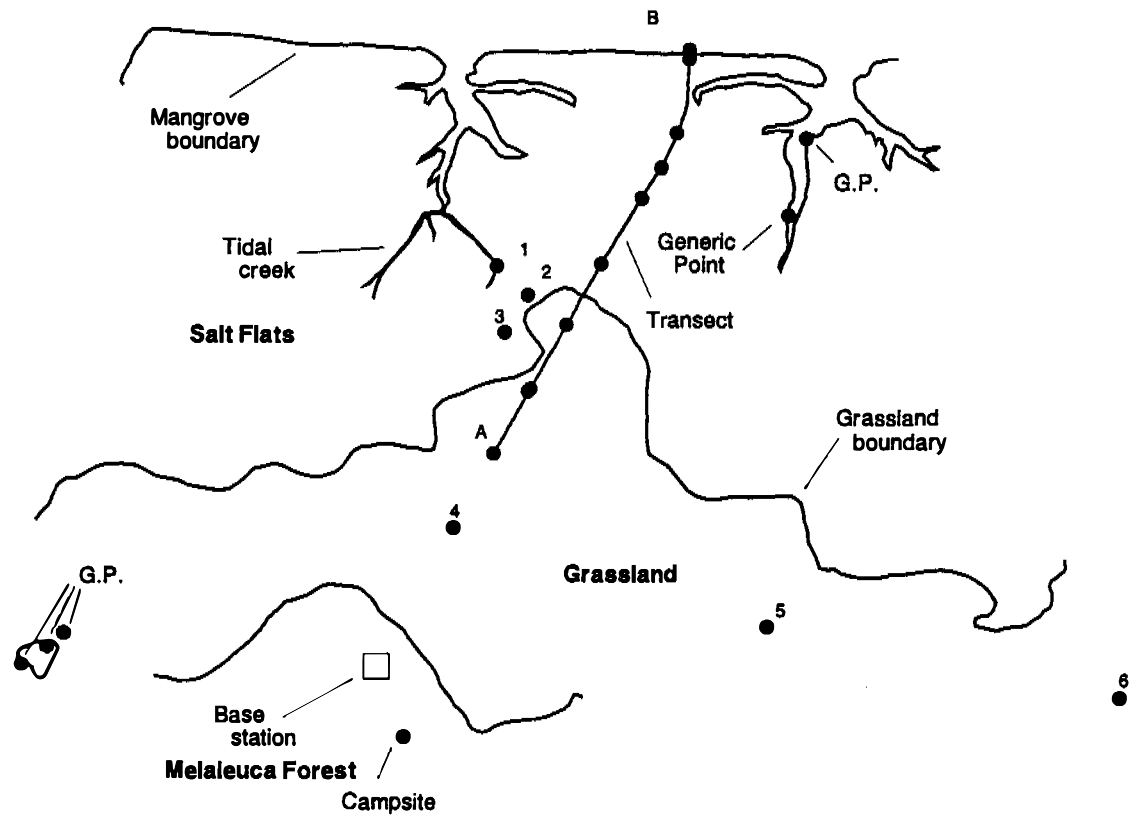
The present distribution of the main morphological features of Point Farewell support the observations of change in the saltwater reach at the East Alligator River estuarine funnel (Figure 3.10). In 1950, the two creek tributaries mapped had each extended from the shoreline as single invading channels, with no branching tributaries (Figure 3.9a). These creeks have since bifurcated into small creek networks, and have been encroached by mangroves (Figure 3.10). The two main tributaries of Point Farewell experiencing rapid rates of extension from 1950 to 1991 (Figures 3.9) have caused extensive areas of *Melaleuca spp.* dieback, as the saline influence of the tidal creeks invaded the *Melaleuca spp.* forest boundary (Plate 3.2).

The intruding tidal creeks at Point Farewell have incised their paths through low-lying coastal salt flat which extends over 500 metres inland in some regions (Figure 3.10). Aerial photographs of the region in 1950 and 1991 (Plate 2.1) indicate that the coastal salt flat has expanded since 1950 at the expense of low-lying grassland. A distinct boundary edge 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 (Figure 3.10). The relative intolerance of the grass to high levels of salt is reflected by the marked difference of soil salinity between the grassland (site 4) and the salt flat (site 3) (Table 3.1).

TABLE 3.1: Soil Electrical Conductivity 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

FIGURE 3.10: EVIDENCE OF SALTWATER INTRUSION, POINT FAREWELL East Alligator River



PROJECTION: Albers Equal Area
SOURCE: This map product was compiled from differential GPS data logged August 1997

Plate 3.2 : Incising Tidal Creek at Point Farewell

Upper reach of a main tidal creek at Point Farewell intruding into an area of *Melaleuca spp.* dieback. New mangroves have established along the upper limit of the channel.

The coastal salt flat is characterised by distinctive cracked clays, which have dried to desiccation in the dry season (Plate 3.3). A feature of the coastal salt flat, numerous chenier ridges lie parallel to the shoreline in slight arc formations, and are testament to the processes of overbank wash and storm surge that occur during each Wet season. The larger ridges can be identified from the 1991 aerial photography in convex arcs flanking the mangrove band along the coastline (Plate 2.1b). Large tree logs and wooden debris were scattered across the salt flat in a similar trend, each strategically positioned perpendicular to the coastline (Plate 3.4). The impact of storm surge and overwash flow on the plain is evident from these configurations.

Plate 3.3 : Clay structure of salt flat at Point Farewell

The salt flat is characterised by dried cracked clays with little surface sediment. Clay surface is smoothed from repeated overwash during Wet season flooding.

Plate 3.4 : Log Debris on salt flat at Point Farewell
The configuration of the large log depicted in the foreground is a feature of the salt flat at Point Farewell. The log lies perpendicular to the East Alligator River, as a result of Wet season storm surge.

3.3.2 Munmarlary

From 1950 to 1991, extensive growth of tidal creeks and mangrove encroachment has occurred within the confines of a palaeochannel swamp on the western flank of the South Alligator River, near Munmarlary (Figure 3.11). In 1950, the tidal creek consisted only of two arm tributaries of a single creek line that extended along the boundary of the palaeochannel. Mangroves had also encroached the downstream limit of the main creek line (Figure 3.11a). By 1975, the southern of the two main tributaries had significantly extended, and had made a second link to the river channel (Figure 3.11a). 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 its first order tributaries (Figure 3.11b). By 1991, 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 creek lines (Figure 3.11b).

See Insert - Figure 2.1

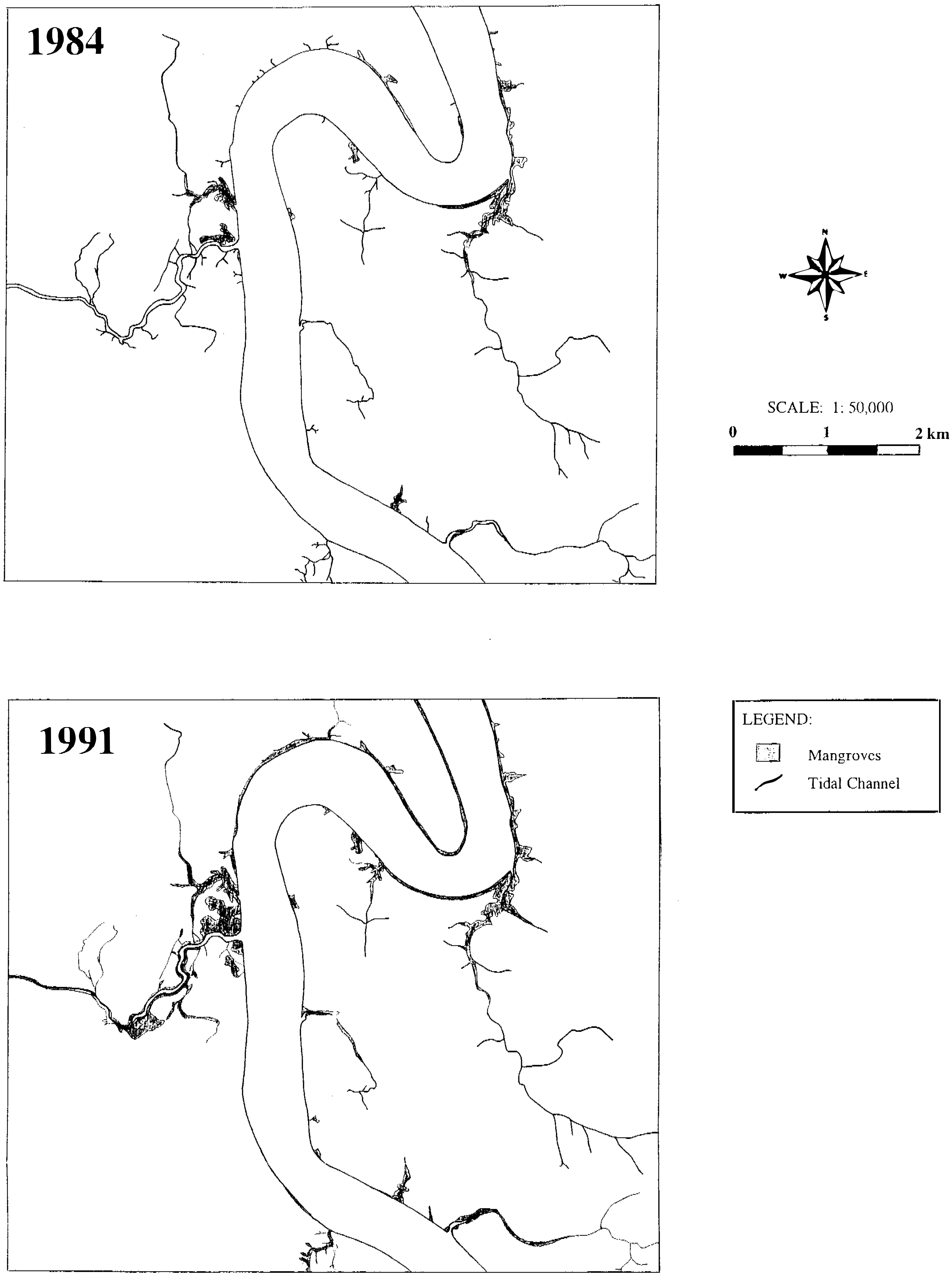


FIGURE 3.11b: Tidal creek and mangrove extension at Munmarlary, South Alligator River, 1984 - 1991.

Source: The tidal creeks and mangrove boundaries were mapped from 1984 and 1991 aerial photography at a working scale of 1: 25,000.

See Insert - Figure 2.1

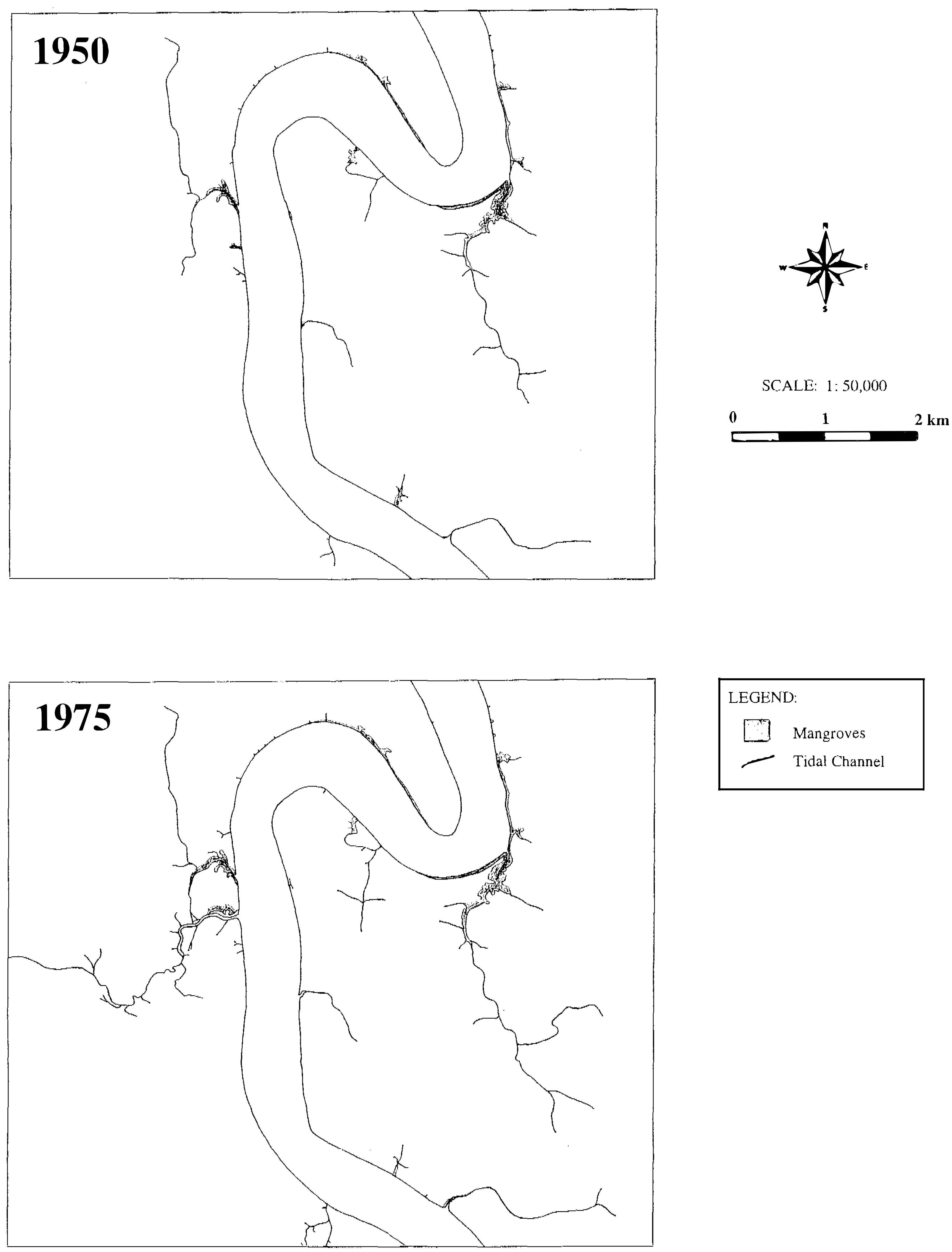


FIGURE 3.11a : Tidal creek and mangrove extension at Munmarlary, South Alligator River, 1950 - 1975.

Source: The tidal creeks and mangrove boundaries were mapped from 1950 and 1975 aerial photography at a working scale of 1: 25,000.

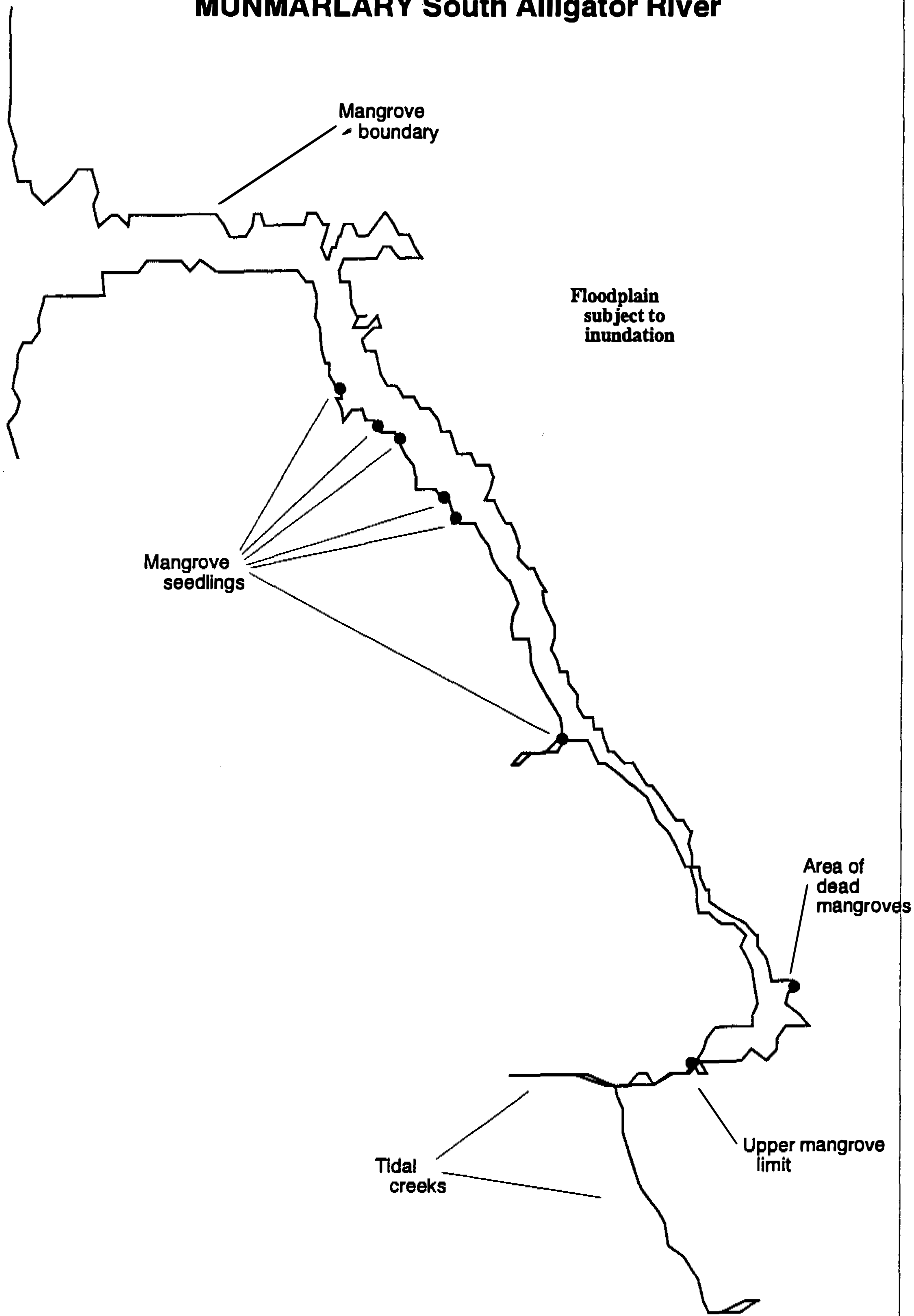
On the eastern flank of the South Alligator River at Munmarlary, relatively little tidal creek growth has occurred over the same time period (Figure 3.11). A single creek line adjacent the palaeochannel in 1950 had shown little significant growth or signs of saltwater intrusion until 1991, when mangroves had colonised the main length of the creek (Figure 3.11b).

The present distribution of mangroves along the creek line are indicative of the recent mangrove encroachment (Figure 3.12). In 1950, the creek line was not colonised by mangroves and had since been densely encroached, despite photographic evidence of little significant creek headward extension. The present upper limits of the tidal creek remain unaffected by mangroves, and patches of dead mangroves were observed flanking the upstream reaches (Figure 3.12 and Plate 3.5).

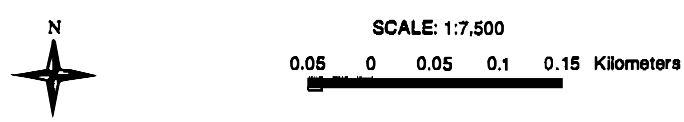
Plate 3.5 : Area of Dead Mangroves, Munmarlary

Area of dead mangroves in the upper reaches of a tidal creek at Munmarlary, indicative of changes in the tidal reach.

FIGURE 3.12: EVIDENCE OF SALTWATER INTRUSION, MUNMARLARY South Alligator River



PROJECTION: Albers Equal Area
SOURCE: This map product was compiled from differential GPS data logged August 1997



The death of mangroves, notably *Avicennia marina* suggest that the creek has experienced a phase of abstraction in the upper reaches. Mangrove encroachment tends to occur in response to expansion of the tidal, or saltwater 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 by this and may be choked 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 line downstream, indicative of the extent of the saltwater reach along the tributary.

3.3.3 Kapalga

From 1950 to 1991, extensive changes have occurred within the Kapalga region on the South Alligator River (Figure 3.13). Of these changes, the most significant development since 1950 has been the extension of one main creek channel into a freshwater swamp, and the subsequent implications of saltwater incursion (Figure 3.14). In 1950, the invading channel appeared as a relatively indistinct creek with few first order tributaries, although it was linked to another creek line (Figure 3.13). By 1975, both creek lines had extended significantly (Figure 3.13). Growth had occurred through the bifurcation of the main tributary arms to form a small tributary network. Mangroves had encroached the linking tributary between the two creek channels. By 1984, the southern channel had experienced rapid headward growth south, and had invaded the low-lying swamp land (Figure 3.13 and Plate 2.3). Little further headward extension occurred by 1991, although rapid mangrove encroachment of the intruding channel and its tributaries was indicative of the expanding saltwater reach (Figure 3.13).

The present distribution of the main morphological features at Kapalga support the observations of past changes in the saltwater reach (Figure 3.15). From 1950 to 1991, an intruding channel invaded the freshwater *Melaleuca spp.* swamp south of the creek mouth, through the process of tidal creek headward extension (Plate 2.3a). The invasion of saltwater has reduced the undulating swampland to salt flat and caused extensive dieback of the surrounding *Melaleuca spp.* paperbark (Figure 3.15 and Plates 3.6 and 3.7). Average electrical conductivity (as a measure of the soil salinity) of the Kapalga salt flat was 3.21 mS/cm. Mangroves had densely colonised the tidal creek, and had encroached most of the channel by 1991 (Figure 3.13). Since that time, the mangroves have encroached further upstream and growth has intruded into areas of dead *Melaleuca spp.* (Figure 3.13). Well-developed single mangroves in the upper reaches of the intruding creek are indicative of the extent of the saltwater reach (Plate 3.8). The absence of new mangrove growth in the upstream reach of the creek suggest that headward extension of

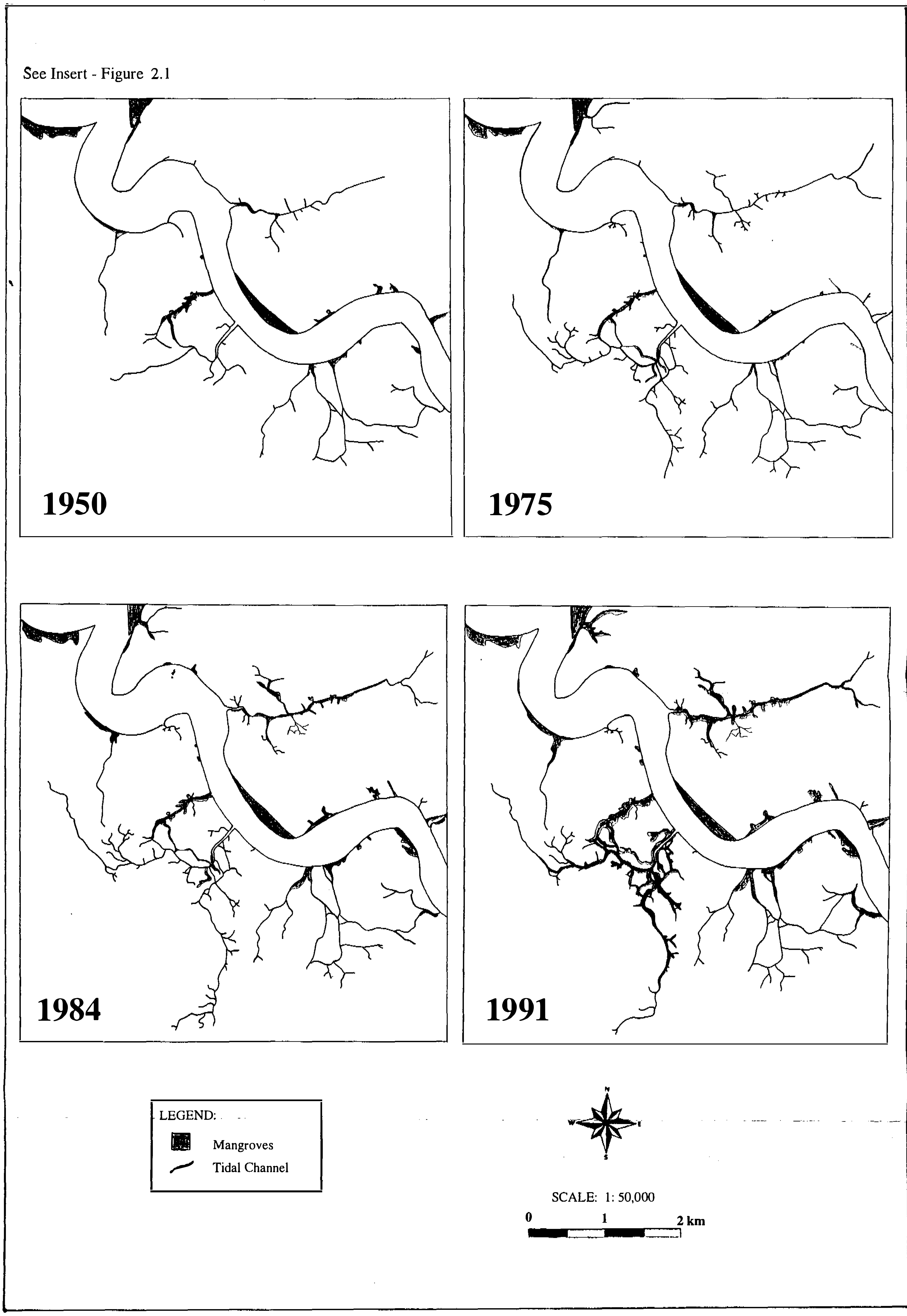
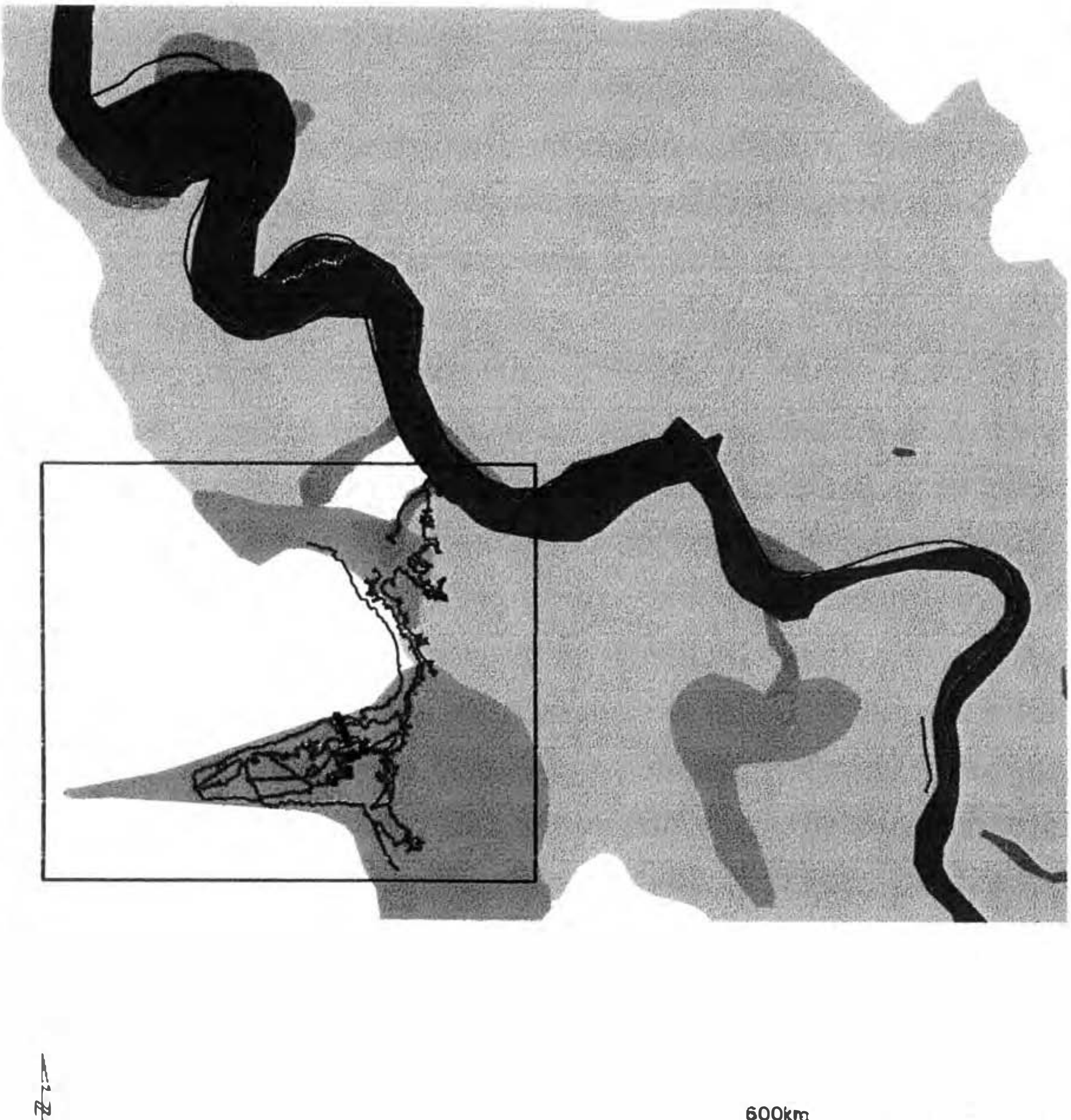


FIGURE 3.13 : Tidal creek and mangrove extension at Kapalga, South Alligator River, 1950 - 1991.

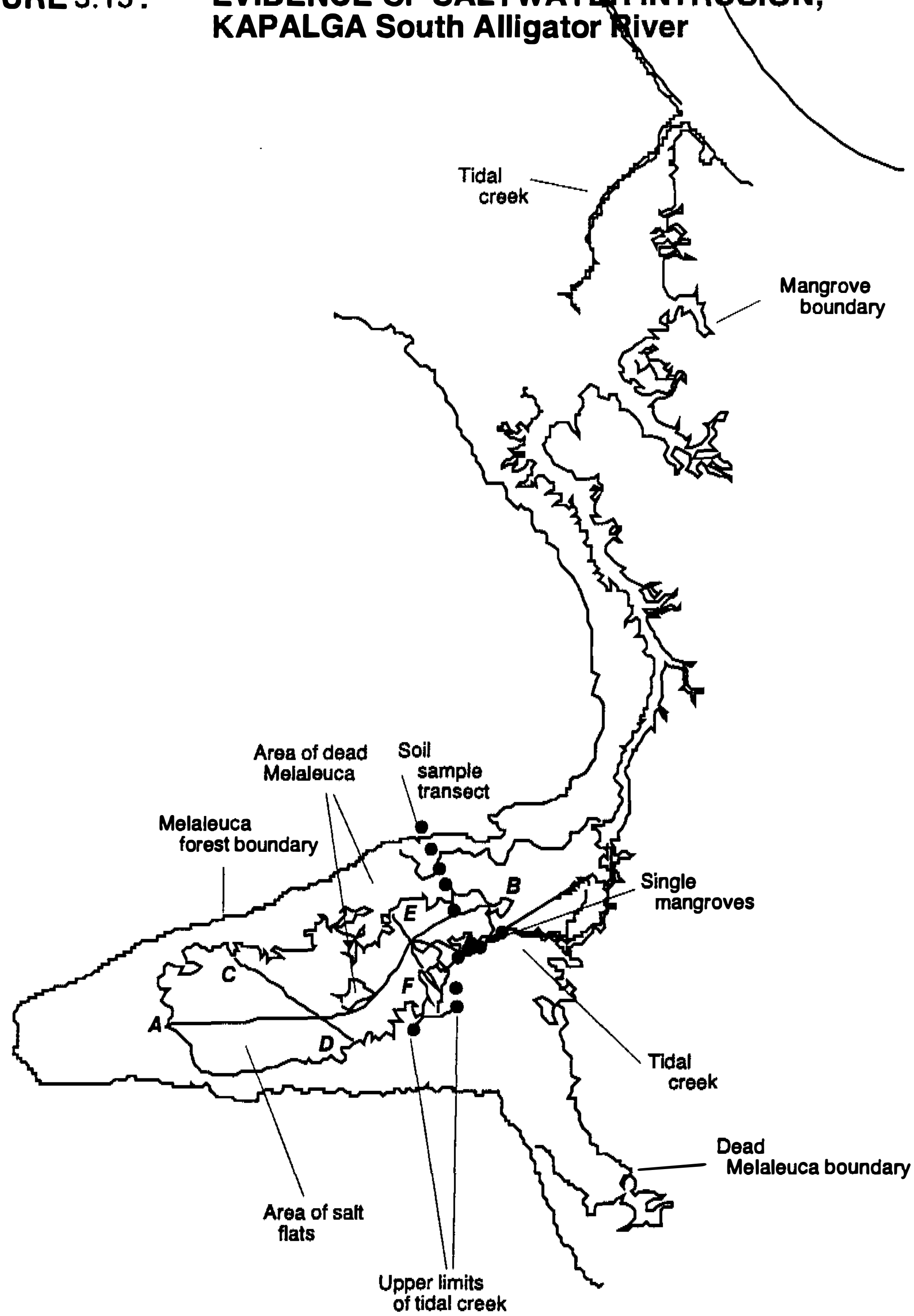
Source: The tidal creeks and mangrove boundaries were mapped from 1950, 1975, 1984 and 1991 aerial photography at a working scale of 1: 25,000.

FIGURE 3.14 : KAPALGA LOCATION



Scale: 1:60,000
Projection: Albers Equal Area

FIGURE 3.15: EVIDENCE OF SALTWATER INTRUSION, KAPALGA South Alligator River



PROJECTION: Albers Equal Area
SOURCE: This map product was compiled from differential GPS data logged August 1997

N

SCALE: 1:20,600
0.25 0 0.25 0.5 Kilometers

Plate 3.6 : Extensive salt flat at Kapalga
Invasion of saltwater at Kapalga has reduced an area of swampland to salt flat. The undulating saline flats are in the middle-ground. Dead *Melaleuca spp*. surround the salt flat, and are testament to the prior freshwater environment

Plate 3.7 : Incising tidal creek, Kapalga
Tidal creek extending into an extensive area of *Melaleuca spp.* dieback. Banks of the tidal creek are flanked with salt tolerant grass. no evidence of new mangrove growth.

Figure 3.8 :Mangrove Encroachment, Kapalga

Single, well-developed mangroves in the upper reaches of an intruding tidal creek.

the tidal creek is not continuing to occur at the rapid rate evident from aerial photography from 1950 to 1991.

Field observations noted that the tidal reach 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 depositional sediment (Plate 3.9). The saltwater reach extended into areas of dead *Melaleuca spp.* on the outskirts of the salt flat (Plate 3.10). 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 capable for channel scouring (Knighton *et al.*, 1991). The scouring action of the tidal

Plate 3.9 : Salt flat Clays, Kapalga

The salt flat is characterised by dried cracking clay soils, overlain with fine deposited sediment.

current is evident at the mouth of the Kapalga creek (Plate 3.11). Although the impact of the large tidal range in the upper reaches is dampened, the incoming tidal front encroached the upper limits of the Kapalga creek tributary at a significant rate of approximately 11 cm/sec during the high spring tide of 7 metres (Plate 3.12).

The rate and extent of the tidal reach at Kapalga suggest that channel development and the process of saltwater intrusion has occurred in response to tidal scour. At exceptionally high tides, saltwater invades the surrounding plains, ponding in areas of slightly lower elevation and forming seepage zones. Though repeated tidal action, the seepage lines would eventually induce more efficient drainage and would have subsequently become susceptible to channel incision.

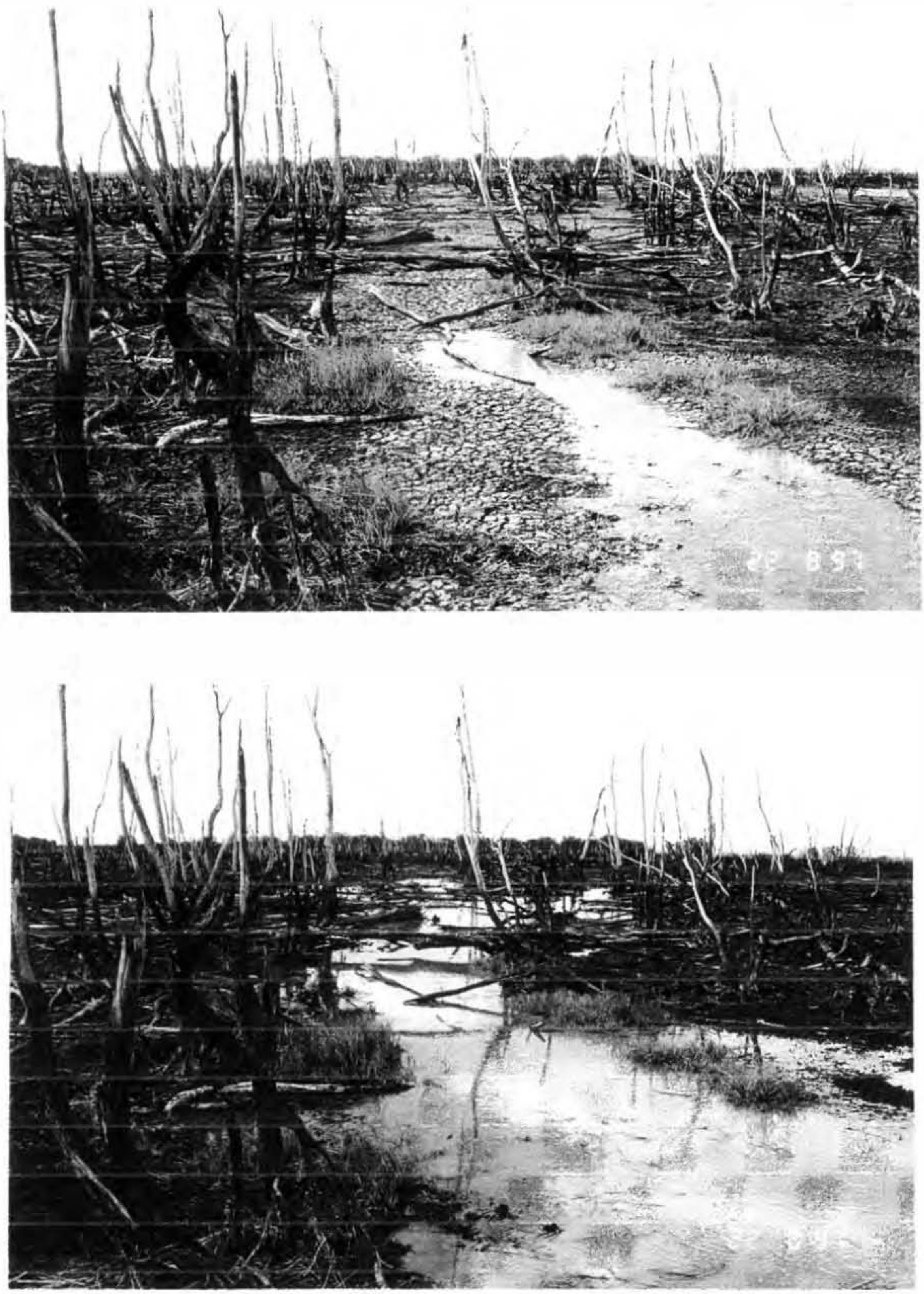


Plate 3.10 : Saltwater intrusion, Kapalga

Saltwater tidal reach breaching the channel, and inundating an area of *Melaleuca spp.* dieback. Photograph sequence taken during incoming high spring tide of seven metres.

Plate 3.11 : Mouth of Intruding Kapalga Creek, at High and Low tide
Dramatic tidal range of the South Alligator River, induces strong currents capable of erosion. Photograph sequence take at high and low tide of the macrotidal cycle.

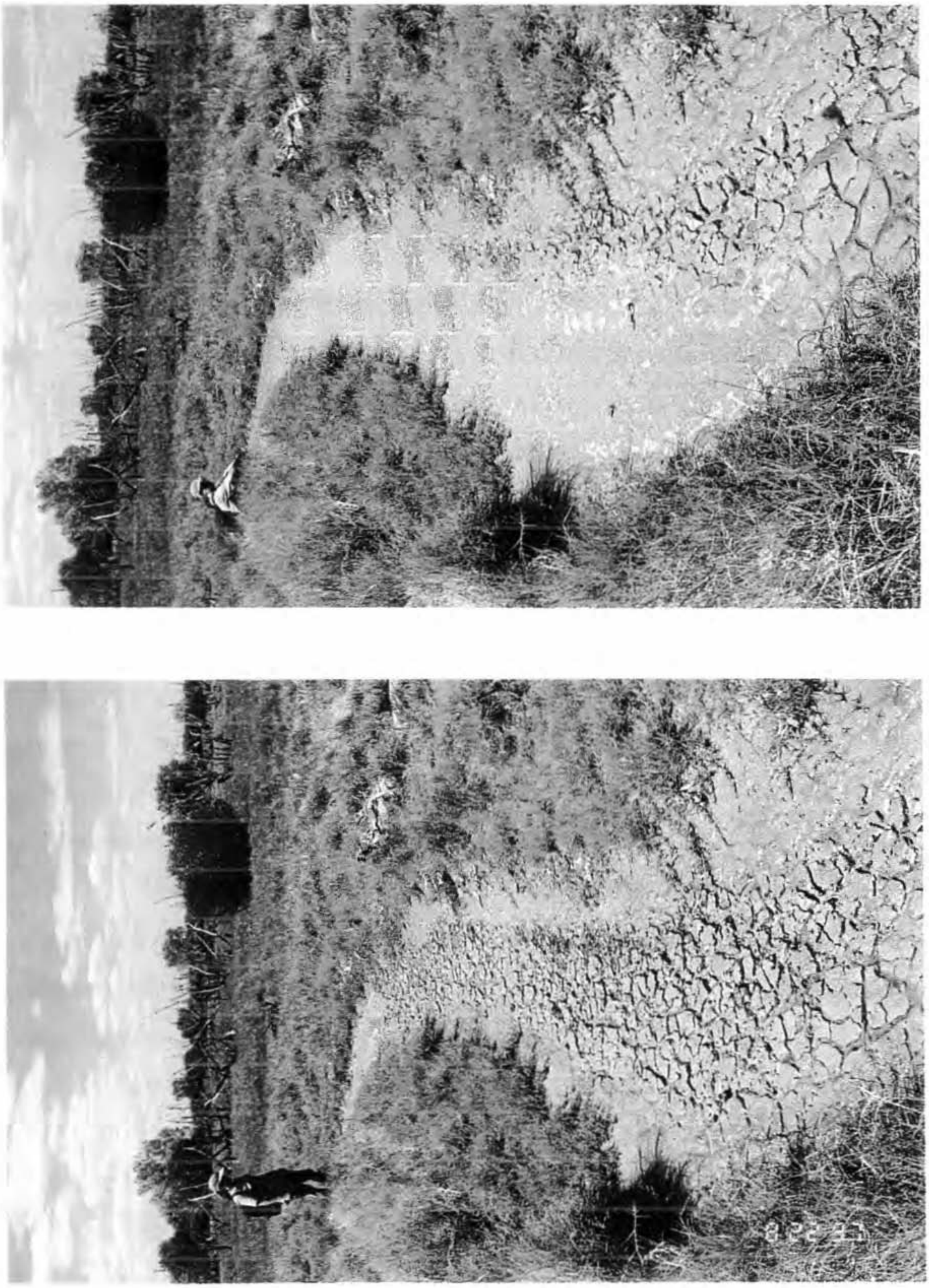


Plate 3.12 : Tidal front, Kapalga

Intruding tidal front during high spring tide of seven metres, indicative of the scouring ability of tidal action. Photographic sequence taken approximately one minute apart.

3.3.4 Growth Trends

Using network magnitude as a measure of network size, Point Farewell has experienced a linear rate of growth since 1950 (Figure 3.16). Alternately, Kapalga and Munmarlary each experienced linear rates of growth until 1975, after which network development became increasingly arrested (Figure 3.16). The rates of network growth varied between the sites, although each followed approximate linear trends (Figure 3.16). From 1950 to 1991, the most rapid increase in network magnitude was at Point Farewell, where the network increased by 89 first order tributaries over 40 years. Over the same time period, from 1950 to 1991, the network magnitudes at Munmarlary and Kapalga increased by 43 and 59 respectively.

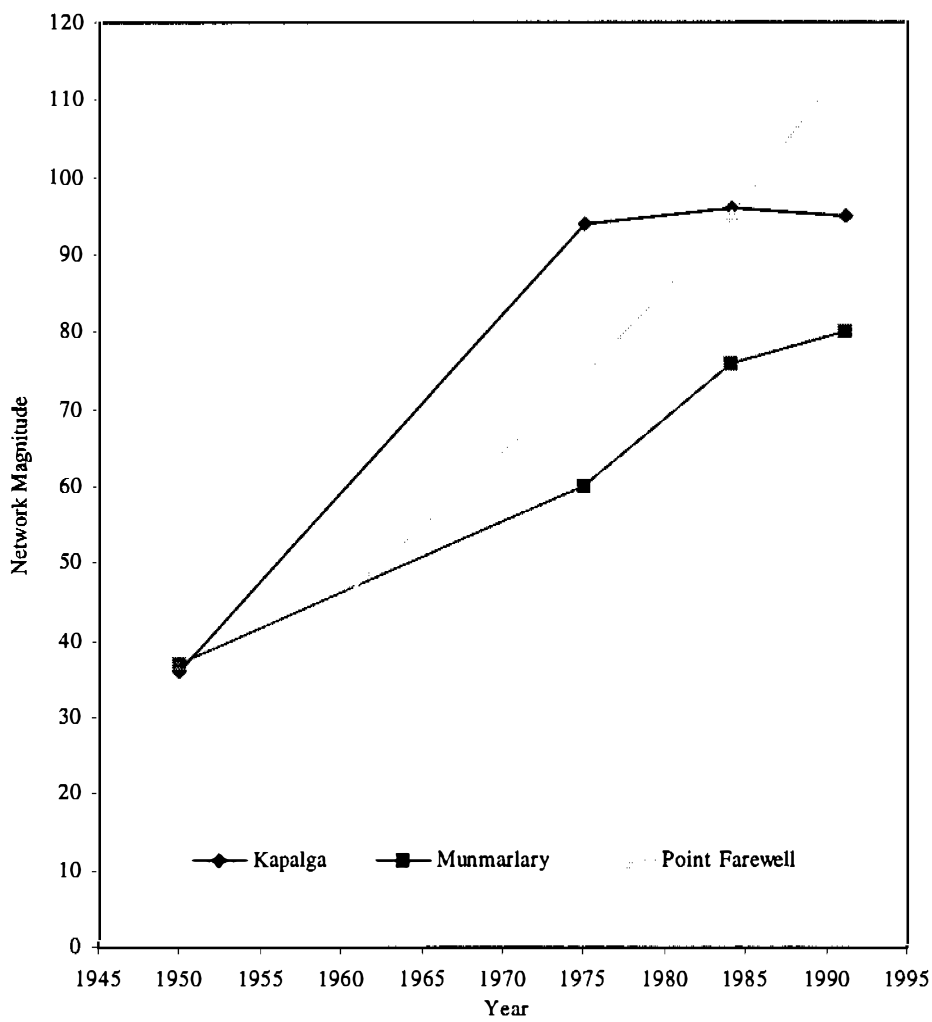


FIGURE 3.16 : Network Magnitude over Time, at Kapalga, Munmarlary and Point Farewell

Point Farewell also attained a higher magnitude (115) as opposed to Munmarlary (80) and Kapalga (95). This may be attributed to the greater tributary development at Point Farewell. Growth at both Kapalga and Munmarlary was dominantly headward extension of one or two main extending channels.

These growth trends are evident from examination of the tidal creek length properties over time (Figure 3.17). Whilst the establishment of external tributaries at Point Farewell followed a linear trend, total creek length over time at Point Farewell increased at an exponential rate (Figure 3.17). This is indicative that tidal creek development at Point Farewell occurred through a combination of both headward extension and tributary growth.

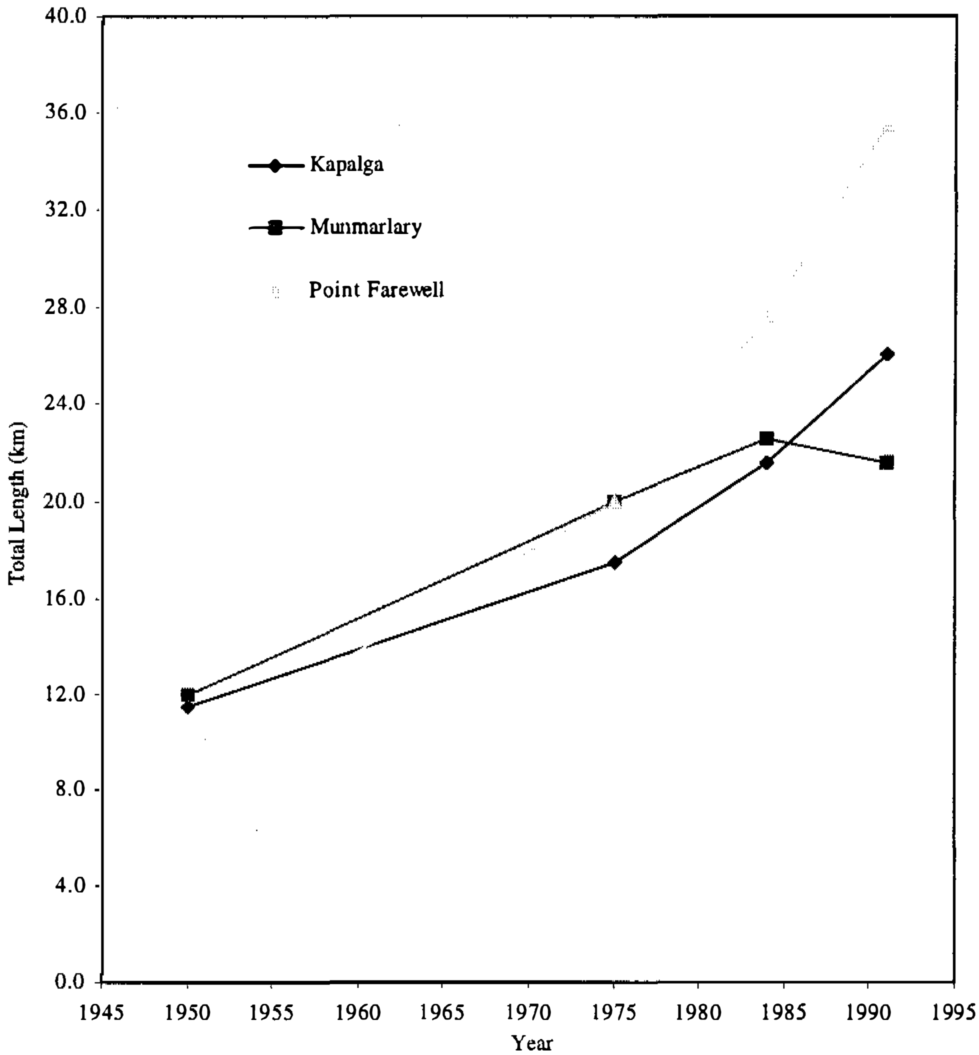


FIGURE 3.17 : Total Creek Length over Time, at Kapalga, Munmarlary and Point Farewell

At Kapalga, total creek length over time increased at a weakly exponential rate, in contrast to the arrested development of network magnitude (Figure 3.17). Using network magnitude and creek length as measures of growth, the Kapalga tidal creeks developed through both headward extension and the growth of tributaries until 1975, after which growth was dominantly by headward extension. Alternate to the growth trends experienced at Point Farewell and Kapalga, the Munmarlary tidal creeks developed through a combination of both headward extension and tributary growth until 1984, after which headward development of creeks became arrested and tributary growth was limited (Figure 3.17).

Despite the variation in creek length growth rates over time, the rate of development at both Point Farewell and Munmarlary was progressively less as stream order increases (Figure 3.18a and b). This is indicative of rapidly expanding networks where first order streams are the primary invaders.

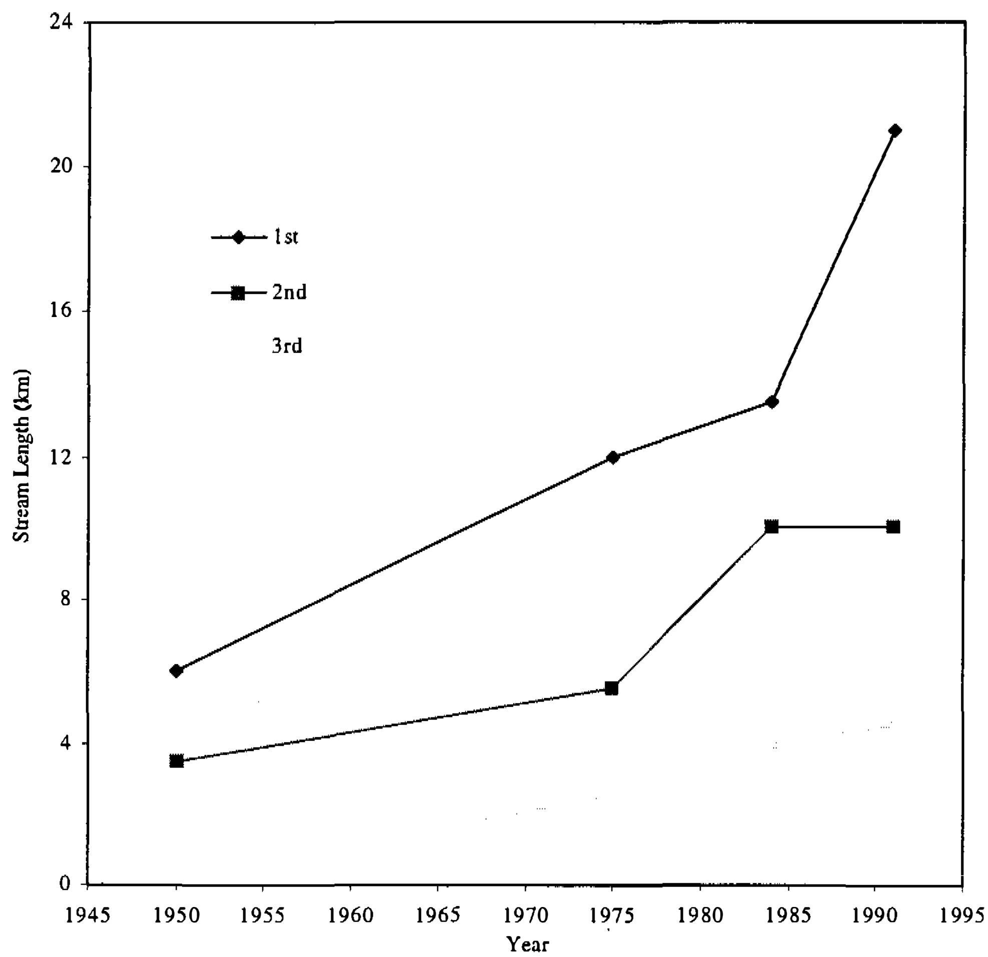


FIGURE 3.18a : Total Creek Length for Different Stream Orders, Point Farewell

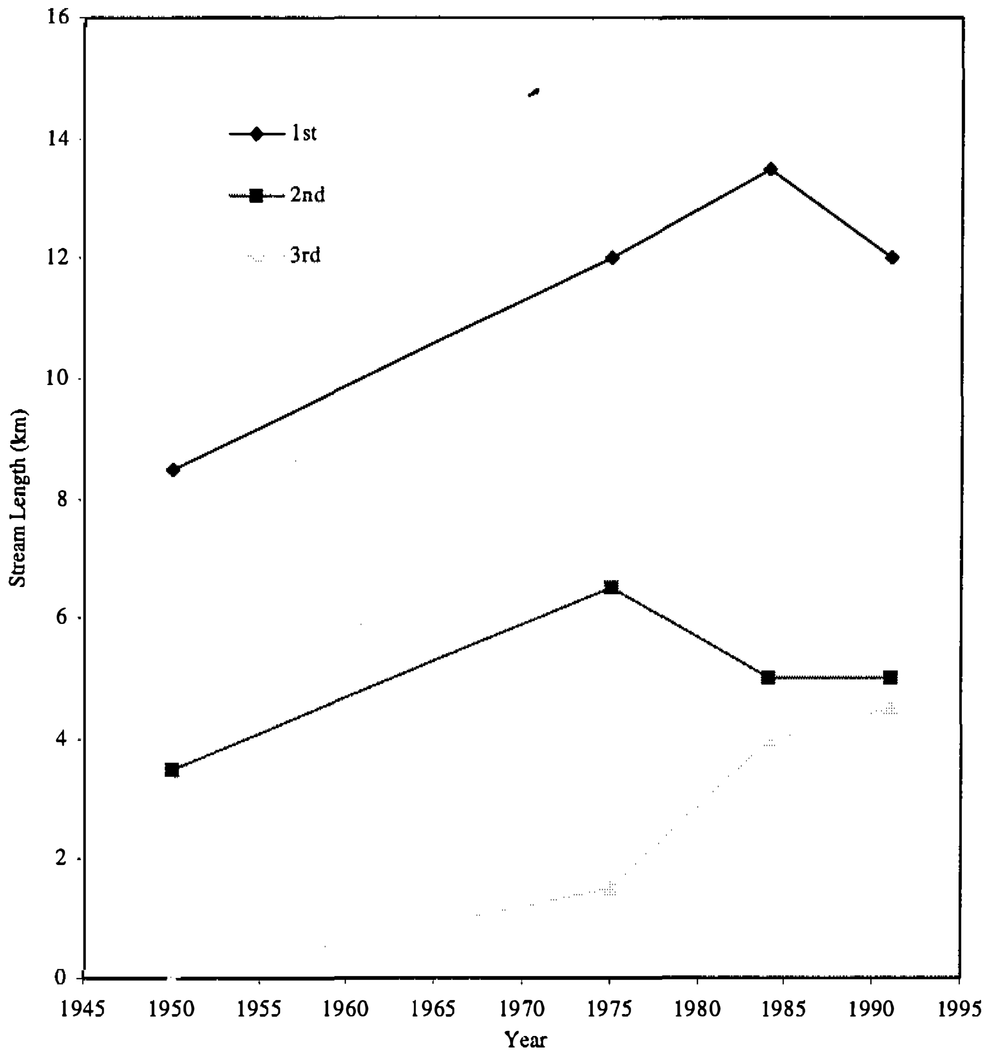


FIGURE 3.18b : Total Creek Length for Different Stream Orders, Munmarlary

Alternate to this trend, the creek length growth rates over time at Kapalga did not decline with stream order (Figure 3.18c). The third order creeks experienced the most rapid rate of development, as befits an increase in the number of first order tributaries.

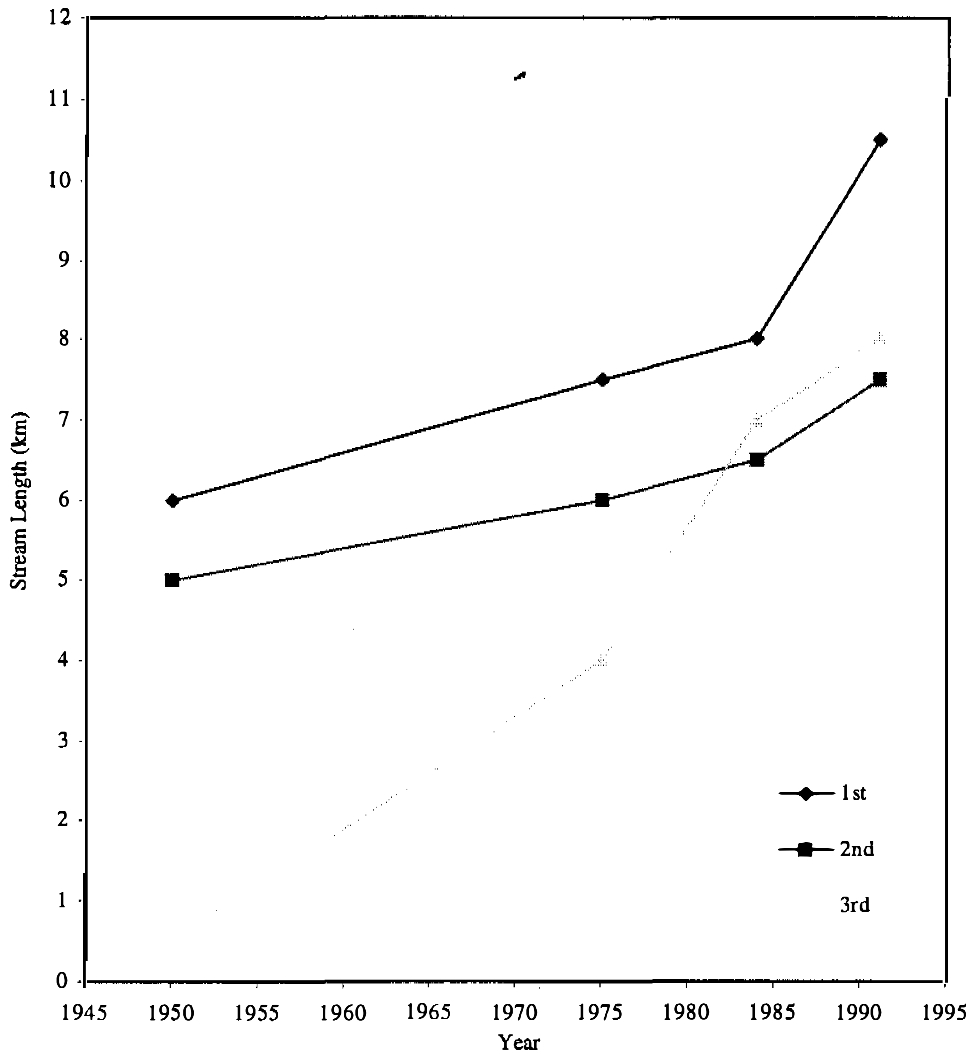


FIGURE 3.18c: Total Creek Length for Different Stream Orders, Kapalga

Point Farewell, Munmarlary and Kapalga have each experienced an exponential rate of mangrove growth, although the rates of change between the field sites varied (Figure 3.19). Mangrove expansion occurred most rapidly at site Munmarlary and Kapalga, with the most significant growth rate occurring post 1975 (Figure 3.19). From 1984 to 1991, the total mangrove area at Munmarlary and Kapalga increased by 1.0 and 0.8 km^2 respectively. Over the same time period, mangrove growth at Point Farewell increased by 0.4 km^2. Despite the varied rates of mangrove growth, by 1991 all three field sites had attained a similar total mangrove area (Figure 3.19).

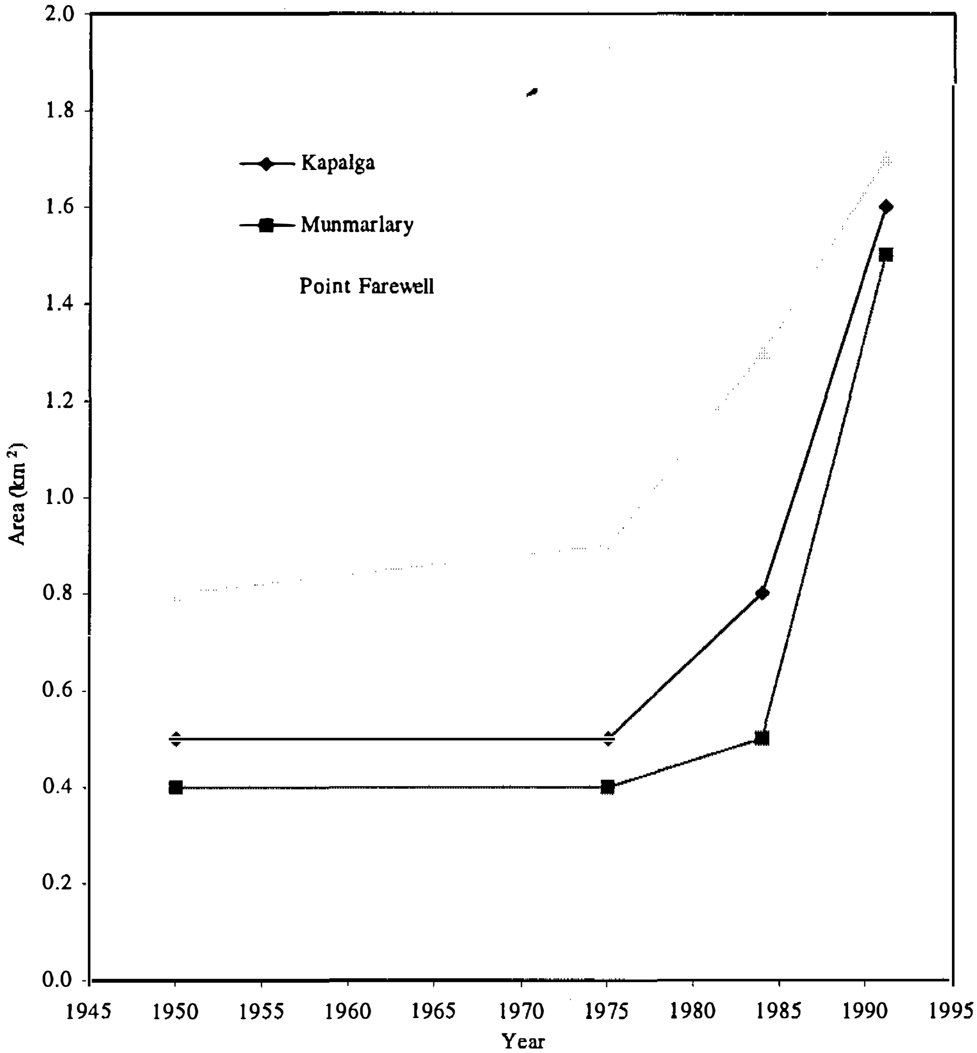


FIGURE 3.19 : Total Mangrove Area over Time, at Kapalga, Munmarlary and Point Farewell.

3.4 OVERVIEW

Changes in the spatial characteristics and distribution of tidal creeks and mangroves in the eastern Alligator Rivers Region indicate that the saltwater reach has expanded along extending creek lines from 1950 to 1991. Analysis of the trends of network growth and mangrove expansion indicate that growth has occurred through both tidal creek headward extension and the development of branching tributaries. Mangrove growth generally occurred along creek lines exhibiting evidence of increased saltwater influence, and susceptibility to inundation. Analysis of the changing spatial characteristics and distribution of tidal creeks and mangroves at the specific field sites indicated that the rates and characteristics of change differed between the field sites. Similarly, field observations and ground mapping data presented morphological evidence of the active trends of saltwater intrusion.

CHAPTER 4 : DISCUSSION AND CONCLUSIONS OF TIDAL CREEK AND MANGROVE EXTENSION IN THE ALLIGATOR RIVERS REGION

4.1 INTRODUCTION

Changes in the spatial characteristics and distribution of tidal creeks and mangroves in the Alligator Rivers Region have been reconstructed from each set of the available aerial photography (1950, 1975, 1984 and 1991) as documentation of recent changes. Analysis and interpretation of changes in network magnitude and length properties of tidal creeks have determined the rate and trends of tidal creek extension on the different river systems in the Alligator Rivers Region. Similarly, the rate and spatial patterns of mangrove colonisation in the Alligator Rivers Region were described for each river system, and paralleled with the rate and growth trends of the tidal creeks. The morphological land surface components in the vicinity of extending tidal creek headwaters of the different channel segments defined by Chappell *et al.*, (1988) were identified and described. Maps of the present site morphologies were constructed at scales less than 1:20,000 as a detailed record of the extent and characteristics of the processes of saltwater intrusion. Field survey and observations were combined with evidence of change from aerial surveys as the basis for a more detailed description of the mechanics of tidal creek extension and saltwater intrusion.

4.2 CHANGES IN THE DISTRIBUTION OF TIDAL CREEKS AND MANGROVES IN THE CONTEXT OF THE WIDER ALLIGATOR RIVERS REGION

The changes in the spatial characteristics and distribution of the tidal creeks and mangroves in the eastern Alligator Rivers Region indicate that the saltwater reach has expanded along extending creek lines from 1950 to 1991. A similar trend of saltwater intrusion has been observed and mapped on the Mary River plains, west of Kakadu National Park. Knighton *et al.* (1992) noted that two main creeks, Sampan and Tommycut Creeks, have experienced rapid tidal creek extension since the late 1930's-early 1940's. Using network magnitude as a measure of the network size, both creeks experienced an exponential rate of growth. Unlike the growth trends which have occurred on the Mary River plain over the same time period, the East and West Alligator Rivers have developed in a linear trend. Similarly, tidal creek development on the South Alligator River and the Wildman River has been only weakly exponential. The exponential growth rate experienced by

Sampan and Tommycut Creeks befits a growth trend that conforms with trends observed in experimental networks (Knighton *et al.*, 1992). Unlike the tidal river estuaries which are characteristic of the Alligator Rivers Region, the Mary River catchment is drained by a number of dendritic tidal creeks that bifurcate from the sea. Therefore, the exponential growth trends observed on the Mary River plains reflect the development of a dendritic network of tidal creeks. Alternately, the Alligator Rivers Region is drained by a series of estuarine channels. Tidal creek growth of each of the main river channels has occurred in localised areas of extension and tributary growth along the length of the river. The predominantly linear trend of network growth determined for the main rivers of the Alligator Rivers Region reflects the absence of large expanding dendritic creek networks, such as that formed on the Mary River plains.

Despite variation in the progress of network expansion between the tidal rivers of the Alligator Rivers Region and their western neighbour, the Mary River floodplains, both floodplains have exhibited similar trends of growth. Knighton *et al.* (1992) noted that the pre-existence of channel lines provided the principle routs for main channel extension on the Mary River. Remnant tidal channels on the floodplain which have been infilled or partially infilled since the Holocene, have formed palaeochannels. Palaeochannels are generally some of the lowest-lying topography within a coastal plain (Woodroffe and Mulrennan, 1993) and hence act as catchments for the development of seepage zones responsible for the initiation of channel scouring. Knighton *et al.* (1992) observed the progress of network expansion on the Mary River plains to have predominantly followed the path of palaeochannels. Tributary growth was confined within the palaeochannel boundaries.

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

Knighton *et al.* (1992) drew further attention to the impact of buffalo swim channels on the trends of saltwater intrusion on the Mary River plains. Noting the susceptibility of pre-existing palaeochannels to saltwater inundation and subsequent incision, large buffalo swim channels formed during the Wet season may become vulnerable to saltwater intrusion and tidal scouring in the Dry season. The distribution of buffalo swim channels in the Alligator Rivers Region have not been indicated on the map compilations of recent changes. Given the relationship observed between main swim channels and tidal creek extension on the Mary River plains, areas of rapid growth in the Alligator Rivers Region may be partly attributed to buffalo activity.

4.3 CONCLUSIONS

The aim of this thesis was to determine the rate, spatial extent and geomorphological character of saltwater intrusion in Kakadu National Park. The gross spatial distribution and growth patterns of changes in the eastern Alligator Rivers Region have been mapped from available aerial photography (1950, 1975,1984 and 1991) in a manner consistent with that adopted by Knighton *et al.*, (1992). Tidal-creek growth was measured as a topological variable of network magnitude. Change in mangrove colonisation over time was measured in terms of the total mangrove area. Documentation of the recent tidal creek and mangrove changes in the Alligator Rivers Region will enable direct comparison of the spatial extent of the estuarine channels in Kakadu National Park with adjacent areas in the Alligator Rivers Region. Prior to this research, comparisons between different regions was difficult due to variations in both scale and format. Subsequently, the maps compiled of recent tidal-creek extension and mangrove encroachment of the Wildman, West, South and East Alligator Rivers may assist in the determination of the geographic extent of the implications of saltwater intrusion, spatial variation in the rates of change, and the area of wetlands affected by salt water intrusion.

Detailed examination of the spatial distribution and growth patterns of tidal creek and mangrove growth was conducted at specific sites exhibiting change. The component morphological units of the specified sites were identified and described from aerial surveys, field mapping and observations. The field sites were selected due to the differing processes or trends of saltwater intrusion dominating different segments of the river. The intrusion of saltwater over the salt flats into the *Melaleuca spp.* forest on the East Alligator River appears to be influenced by the impacts of storm surge and overbank flooding. Alternately, the headward extension of one channel tributary into the Kapalga salt flats, off the cuspate segment of the South Alligator River, is testament to the incising processes of tidal scour causing tidal-creek extension. In contrast to these trends, the small tributary branching from Munmarlary on the sinuous segment of the South Alligator River has exhibited little tidal creek growth. The spatial distribution and patterns of mangrove colonisation along the Munmarlary creek line suggest that the tidal creek headwaters may be abstracting, indicative of a decline in the tidal influence. Detailed descriptions of the morphological units of each site have provided the baseline for future measurement and assessment of the change.

Saltwater intrusion through tidal-creek extension has been identified as the major coastal management problem in the Alligator Rivers Region, incorporating Kakadu National Park as its eastern component (Bayliss *et al.*, 1995). Whilst the trends of saltwater intrusion have been well documented in the literature for the South Alligator River and Mary River plains, the geographic extent of the problem, and the spatial variations in the rates of change had not been determined in detail. The research described herein has identified and documented areas at risk, as well as the changes which have occurred over the last 50 years.

4.3.1 Future Research and Monitoring

This research has acted to complete documentation of the trends and extent of saltwater intrusion of the wider Alligator Rivers Region. Future research should incorporate continued monitoring programs to record future changes, processes and rates of saltwater intrusion across the wider Alligator Rivers Region. Whilst the extent of the problem has been well defined in the literature, and the trends of saltwater intrusion are generally well-understood, little research has addressed the mechanics or processes of saltwater intrusion. This research has described the present morphological components of field sites from different river segment through field observations and detailed mapping. These sites should be adapted as a basis for future monitoring of changes related to the impact of saltwater intrusion. Given the threat saltwater intrusion poses on the freshwater wetlands within the Alligator Rivers Region, a future monitoring program is an essential task for management, in order to delineate areas at risk.

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APPENDIX 1

Sources and Coverage of Aerial Photography

Date	Scale	Height	Colour	Source	Coverage
1950	1: 50,000	25,000'	B/W	AUSLIG	Arnhem Highway, north to coast
1975	1:25,000	12,500'	Colour	Aerial Surveys	Arnhem Highway, north to coast; includes South and East Alligator Rivers
1984	1:25,000	Unknown	Colour	AUSLIG	Kakadu National Park
1991	1:25,000	13,000'	Colour	AIReSEARCH	Kakadu National Park

APPENDIX 2

Field Notes at Kapalga - Monday, 18 August 1997

Mouse and Ray set up base station at a known geodetic site (Kapalga NTS 018) at approx. 2.00 pm

Steph, Ray and Mouse drove by 4WD vehicles and quads to the Kapalga site, which 1950 and 1975 aerial photographs indicate to have once been a Melaleuca swamp. As evident on the 1991 photos, a tidal channel and associated mangroves now extends into the area that had been populated by these trees.

Steph mapped the saltflat areas (comments: no trees, dead or alive) with the GPS rover receiver mounted on a quad bike. Included the boundary of small dead tree pockets in the centre.

Mouse and Ray surveyed the site addressing the practicalities of mapping creek lines and mangrove boundaries etc. Ray took photos of features of the site - creeklines, mangroves, saltflats......., and 'apparatus'.

Steph and Mouse ran up the creekline from the upstream extent of the channel with the GPS on the quad, placing a point reading at the end of each tributary; and at single mangroves. The creekline was characterised by black, muddy creacked clays, wetted at high tide and outlined by a grass levee bank. The creekline ended in an area of dead paperbark.

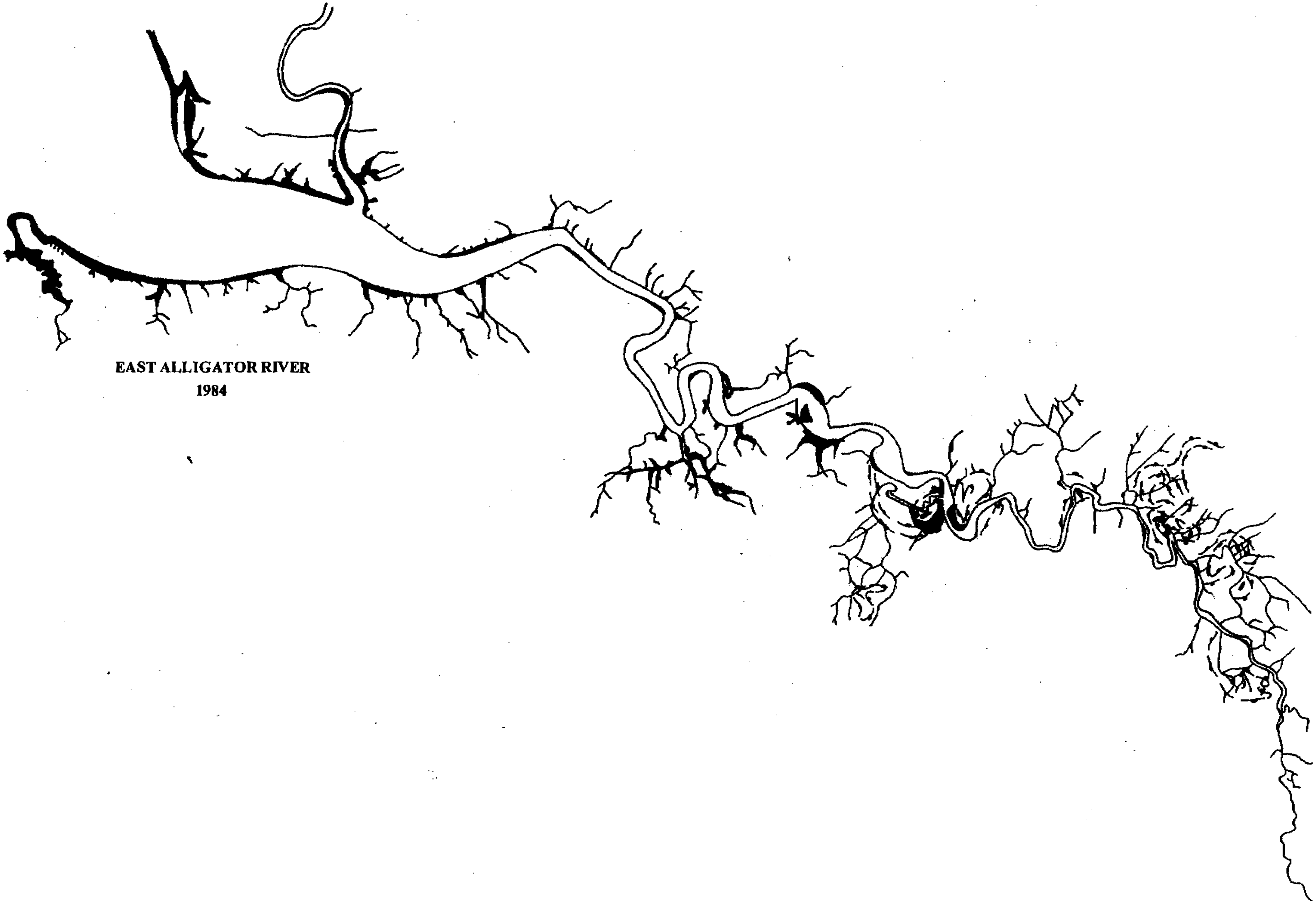
Mouse ran two orthogonal transects across the bare saltflat area with the GPS on quad in order to see if any depression is apparent.

Ray and Steph walked a transect - N/W from the creekline (Generic point; comments: MAN 3) to the Melaleuca forest. Soil samples collected from - 10cm depth from <u>eight sites</u> along the transect:
S1 levee bank, S1creek bed, S1 N/W side of bed under mangrove, S2 saltflat, S3 dead trees,
S4 *Eleocharts dulcis* (reed) patch, S5 *Psuedoraphis spinescens* (grass) patch, and S6 Mel forest.
Mouse took a GPS reading at each sample site. EC and possibly particle size analysis to be conducted on samples back at *eriss* or UWA.

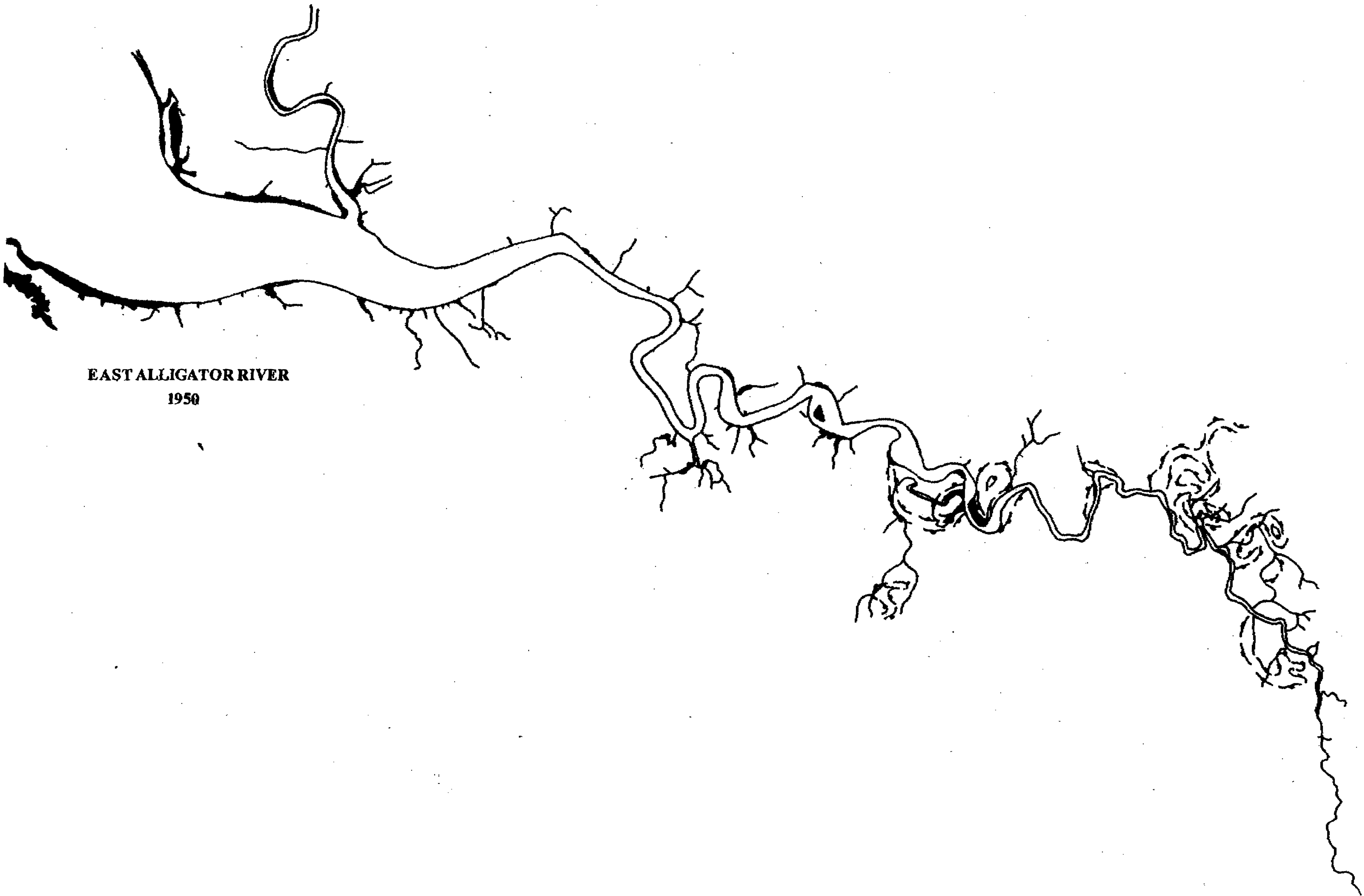
Departed the Kapalga site and dismantled the base station, leaving tripod standing for the following day. Returned to *eriss* - 6.30 pm. Mouse down-loaded data and began processing.

General Observations:
saltflat areas:
- cracked clays, areas of reed *Eleocharis dulcis.*
- scattered logs in random directions (transition between dead paperbark boundary and defined saltflat boundary)
- pools of water (freshwater / saltwater?)
- evidence of pig diggings

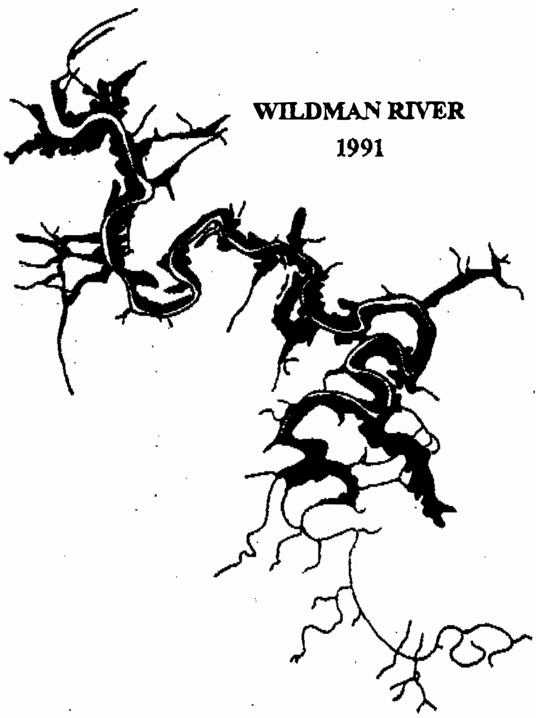

EAST ALLIGATOR RIVER
1991

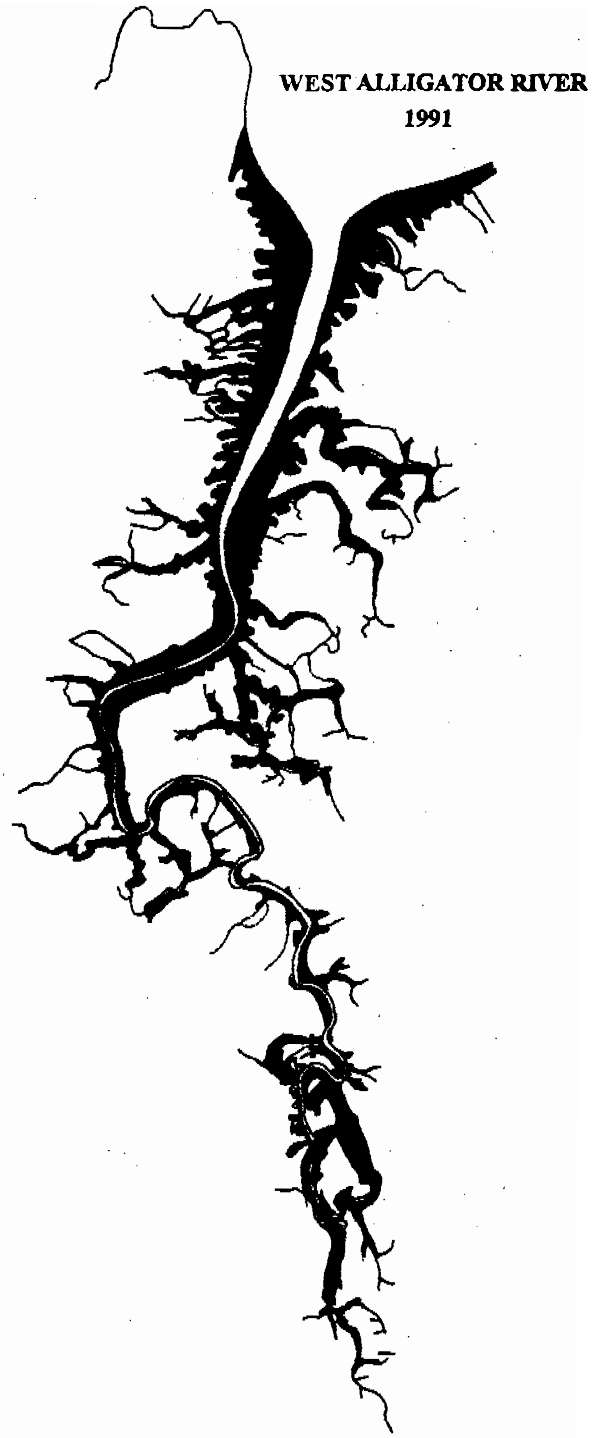

EAST ALLIGATOR RIVER
1984

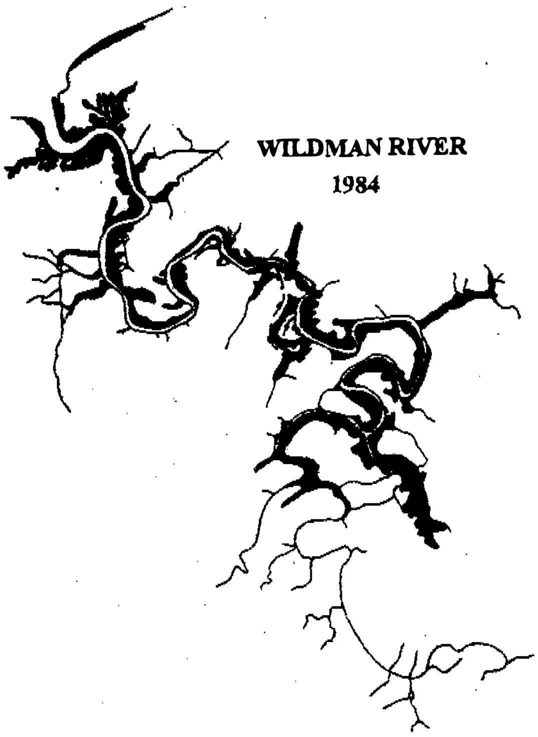
EAST ALLIGATOR RIVER
1975



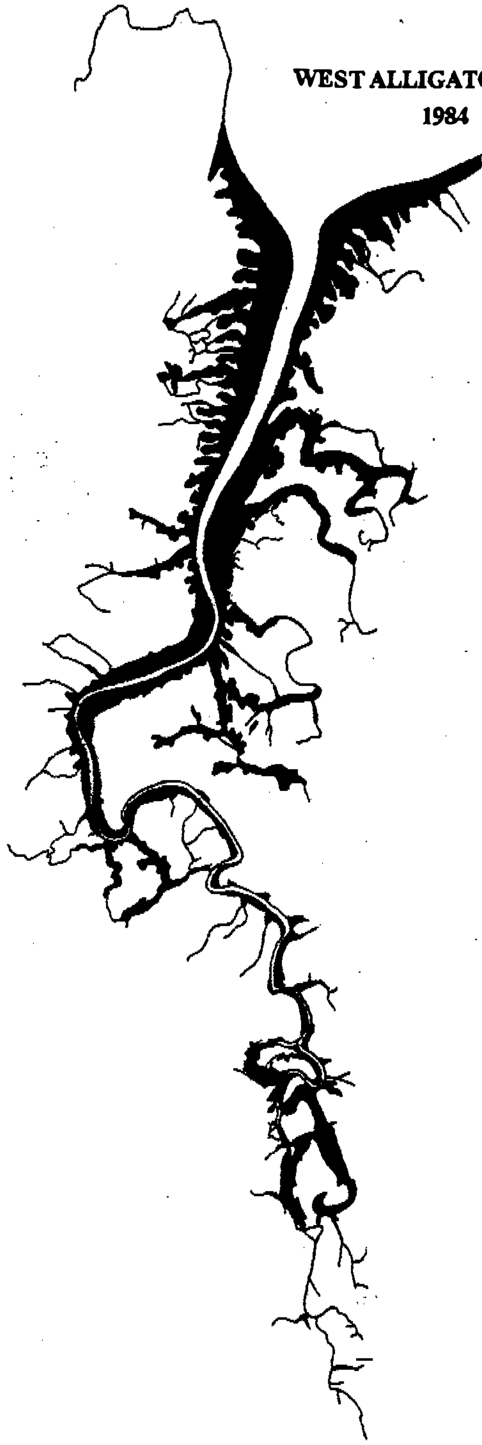
EAST ALLIGATOR RIVER
1950


WILDMAN RIVER
1991

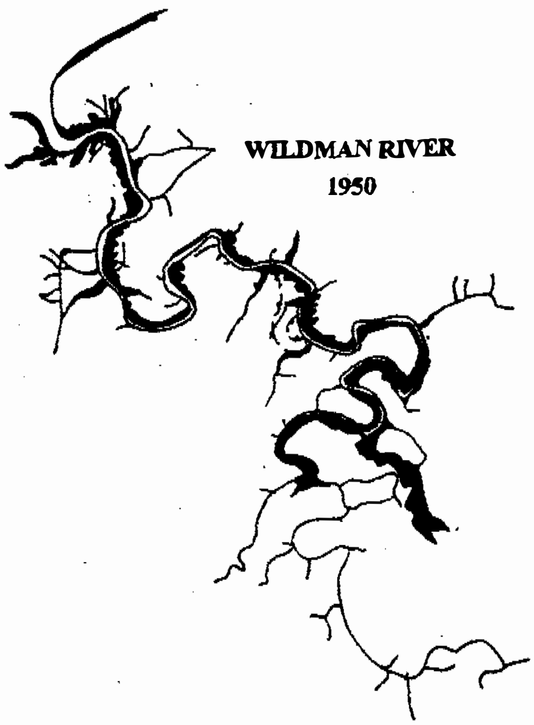

WEST ALLIGATOR RIVER
1991

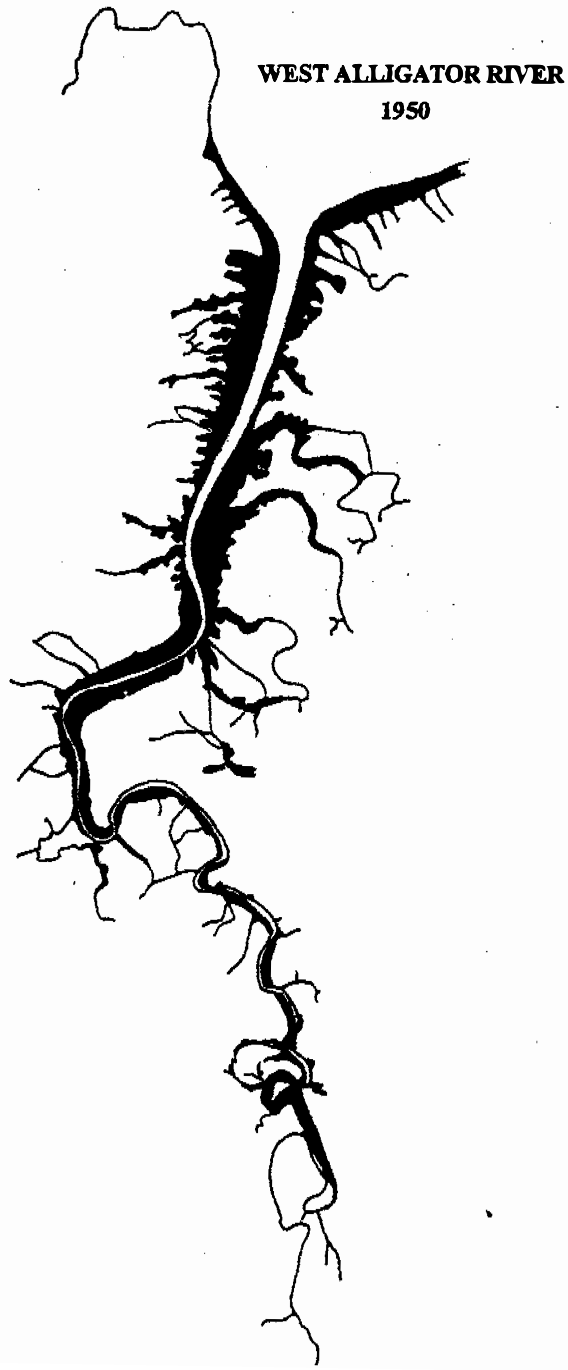


WILDMAN RIVER
1984

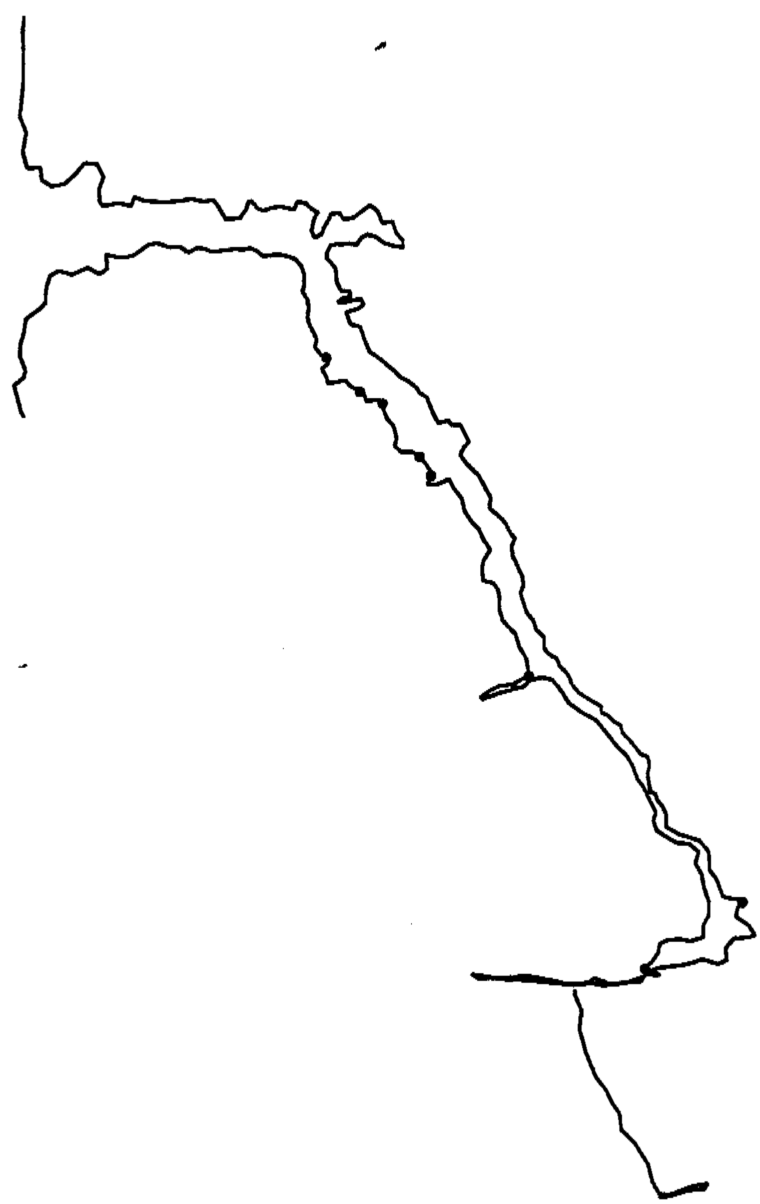


WEST ALLIGATOR RIVER
1984


WILDMAN RIVER
1950

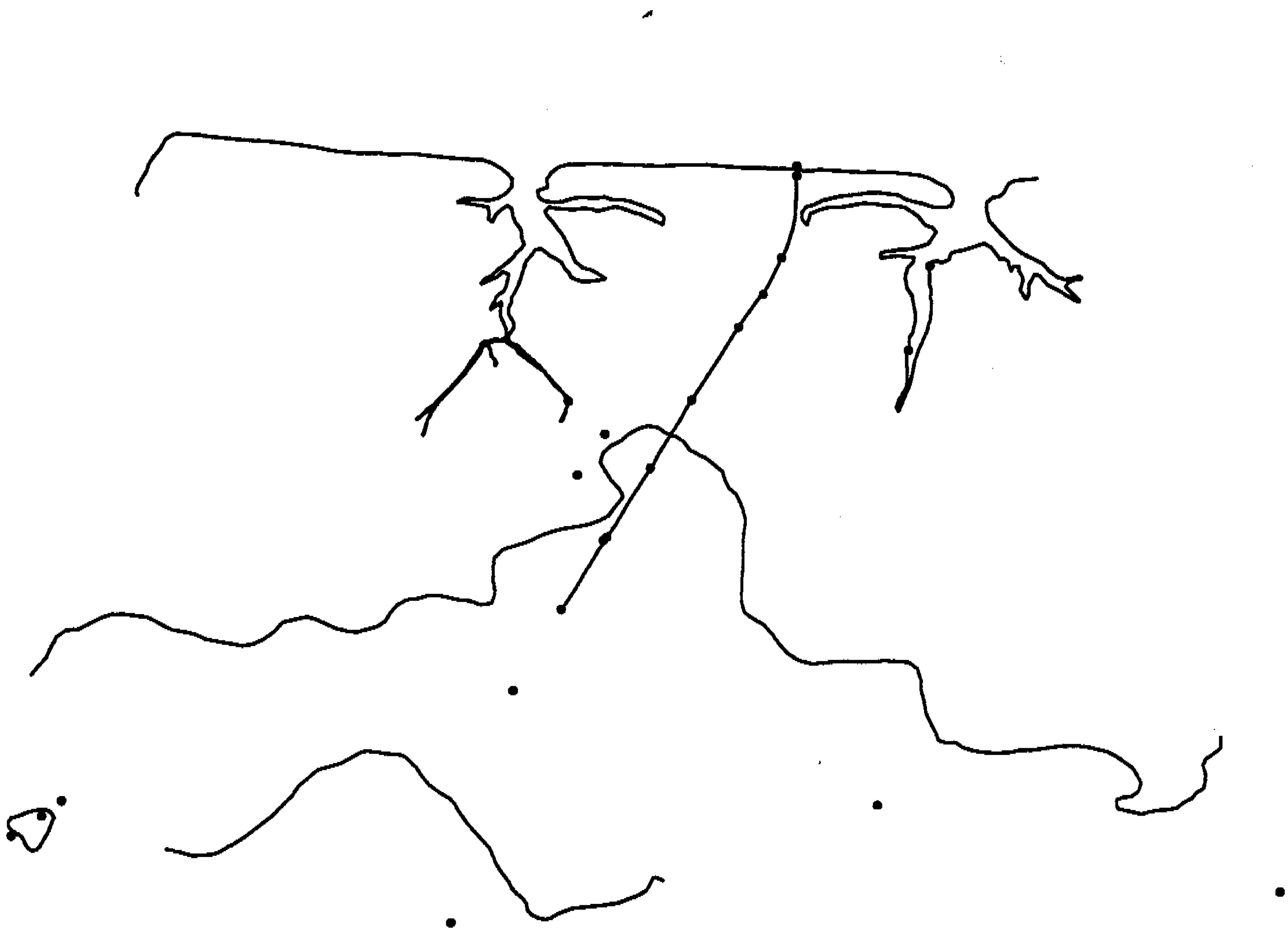

WEST ALLIGATOR RIVER
1950

Tidal Creek Extension, Munmarlary



Scale: 1:8000
Projection: Albers Equal Area

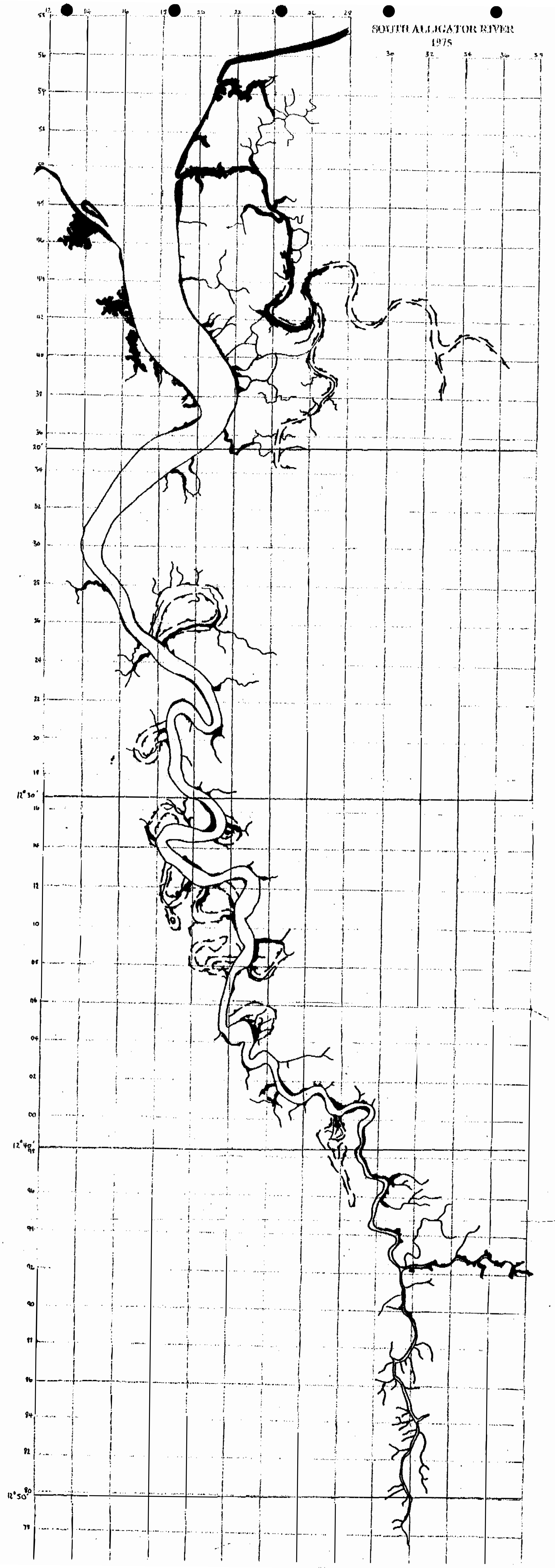
Tidal Creek Extension, Point Farewell



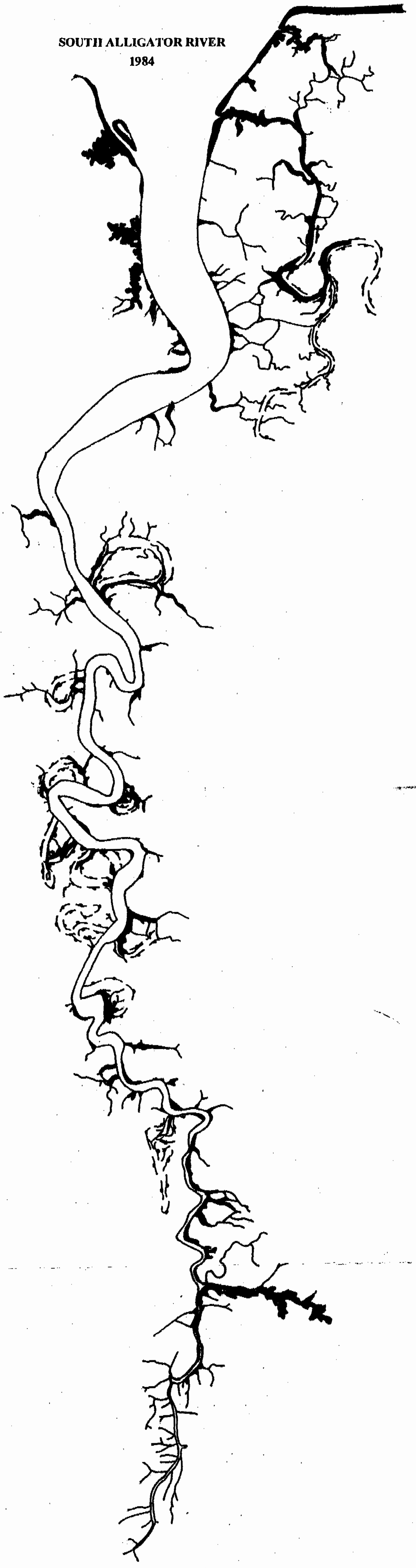
Scale: 1:16,000
Projection: Albers Equal Area

Tidal Creek Extension, Kapalga

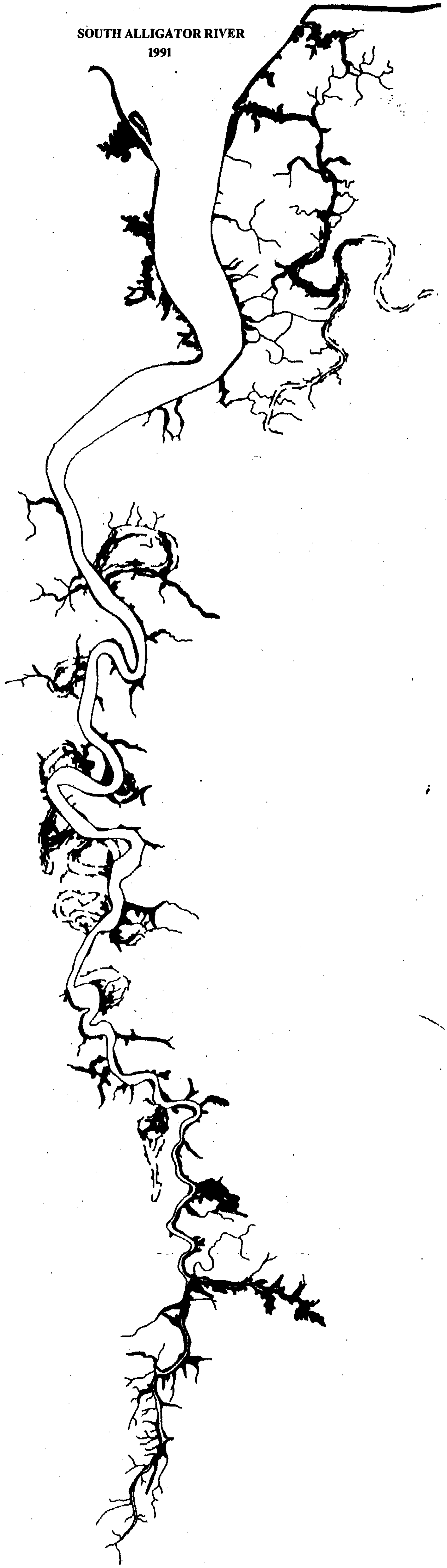
Scale: 1:45,000
Projection: Albers Equal Area

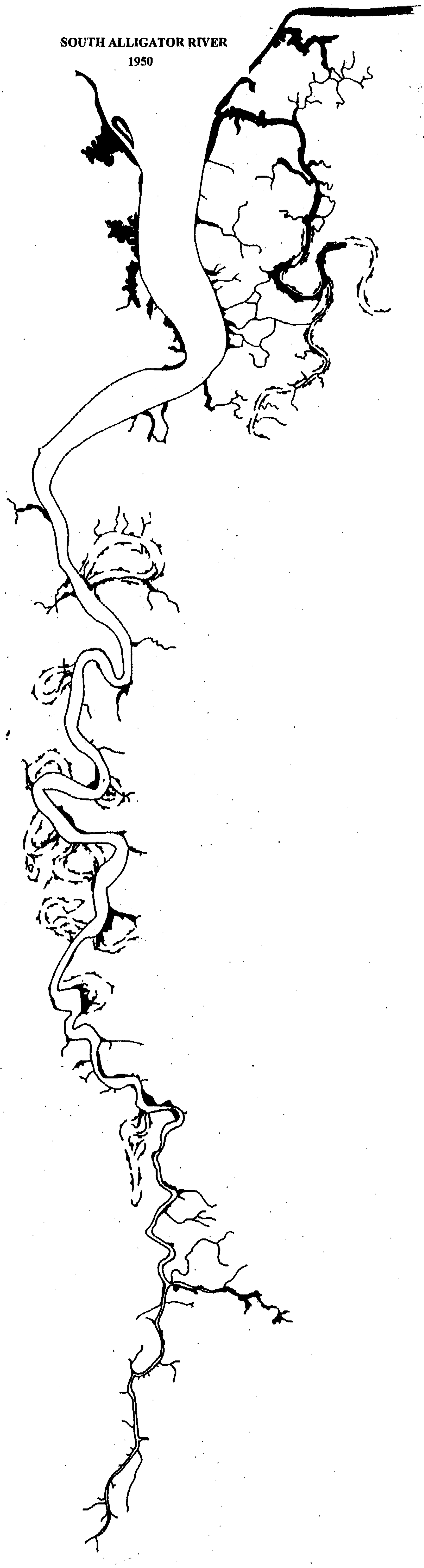

SOUTH ALLIGATOR RIVER
1975
20'
12°30'
12°40'
12°50'

SOUTH ALLIGATOR RIVER
1984



SOUTH ALLIGATOR RIVER
1991




SOUTH ALLIGATOR RIVER
1950