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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

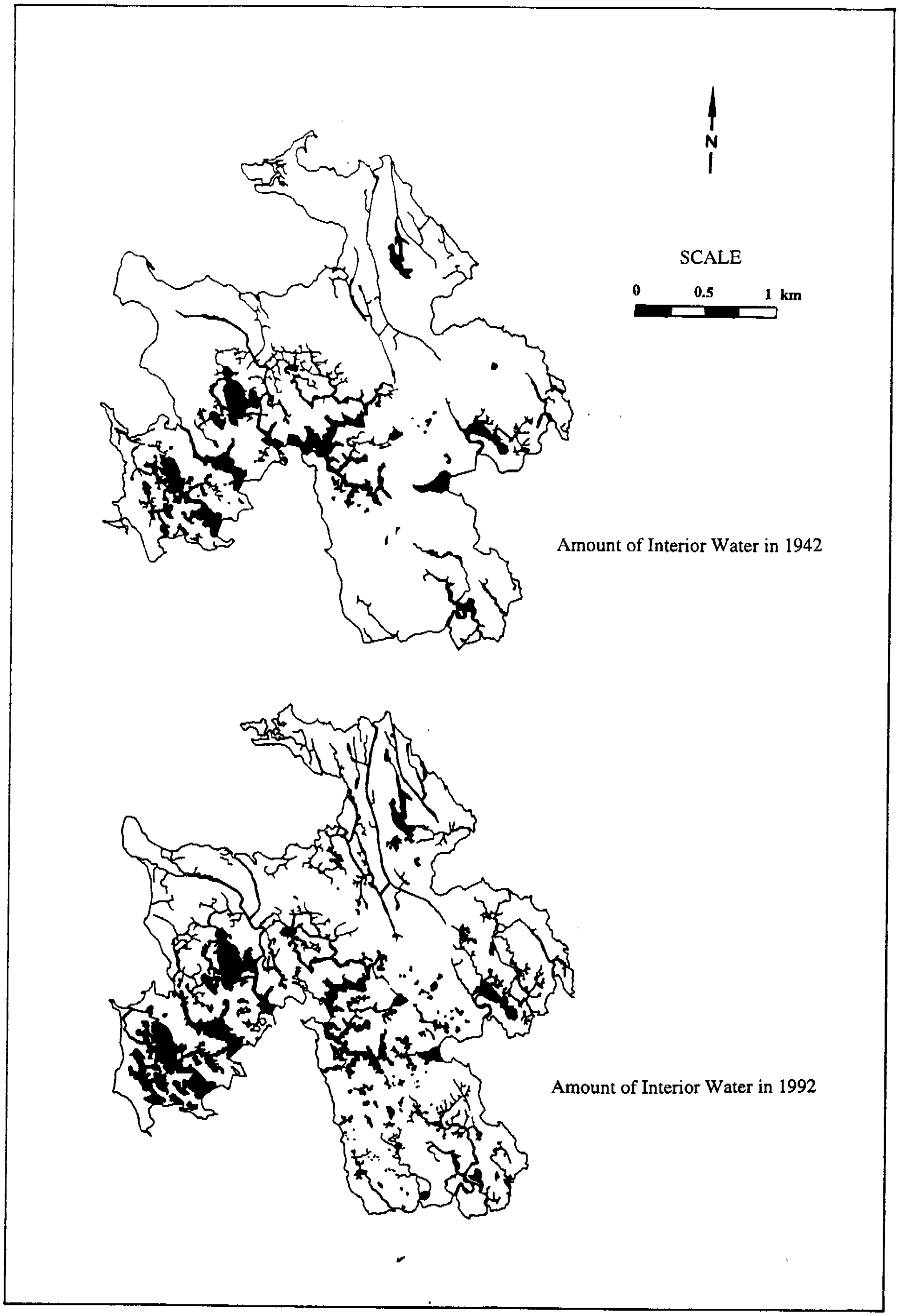

FIGURE 1.1 : Drainage and pond expansion on Bloodsworth Island, Chesapeake Bay, 1942 - 1992 (Downs *et al.*, 1994).

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

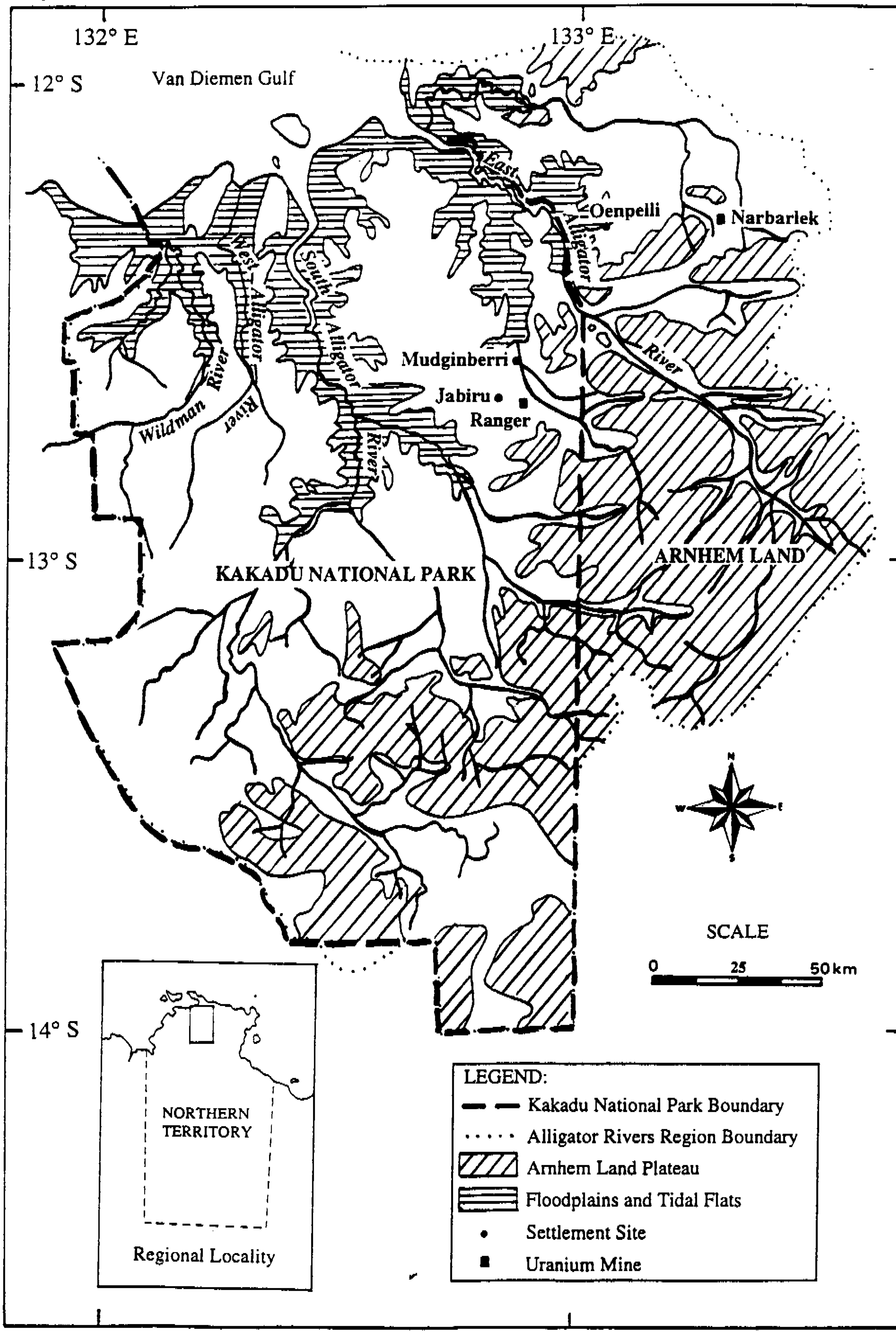

FIGURE 1.2 : Locality Map of Kakadu National Park

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,

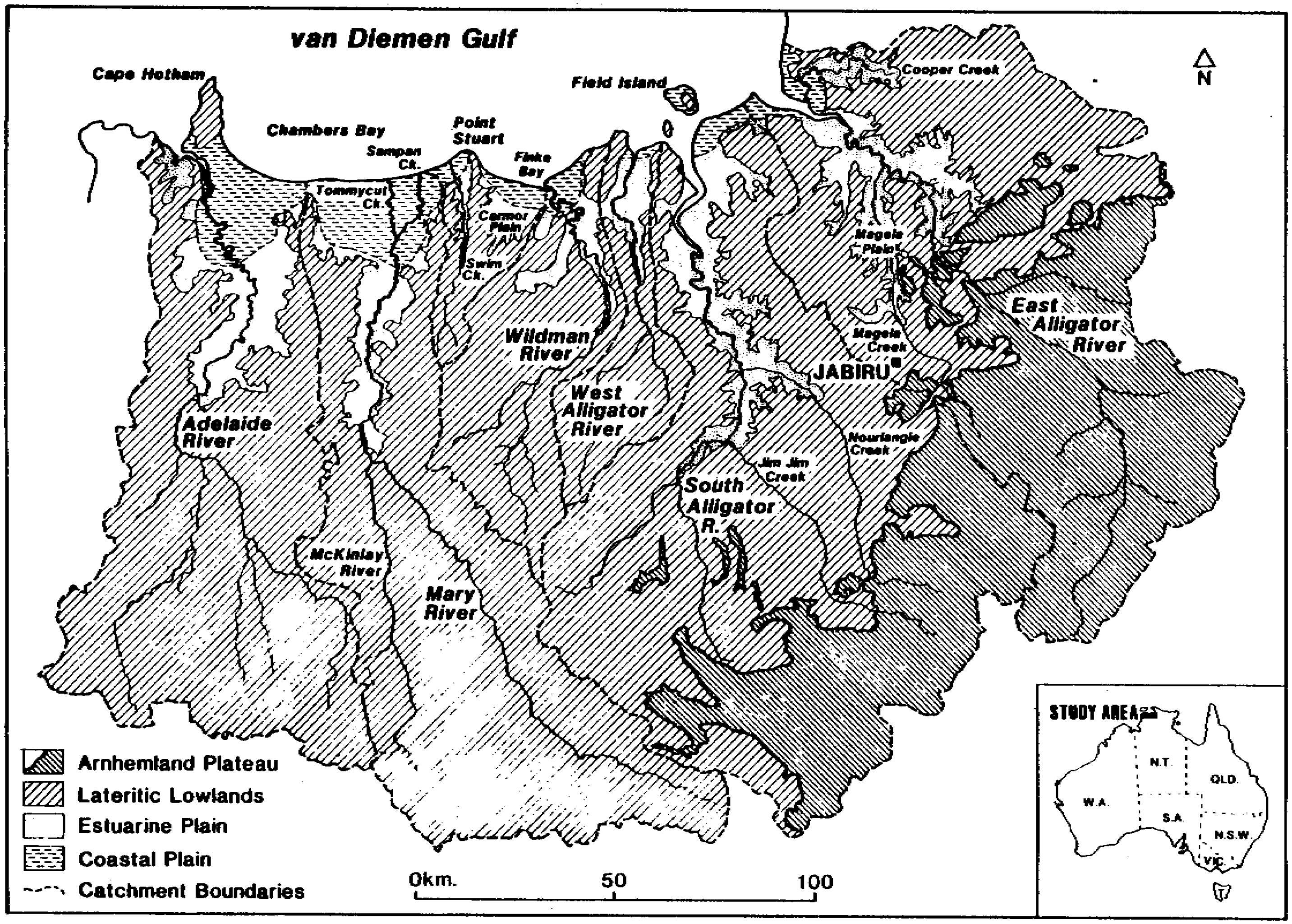

FIGURE 1.3 : Locality Map of the wider Alligator Rivers Region
(Woodroffe and Mulrennan, 1993).

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

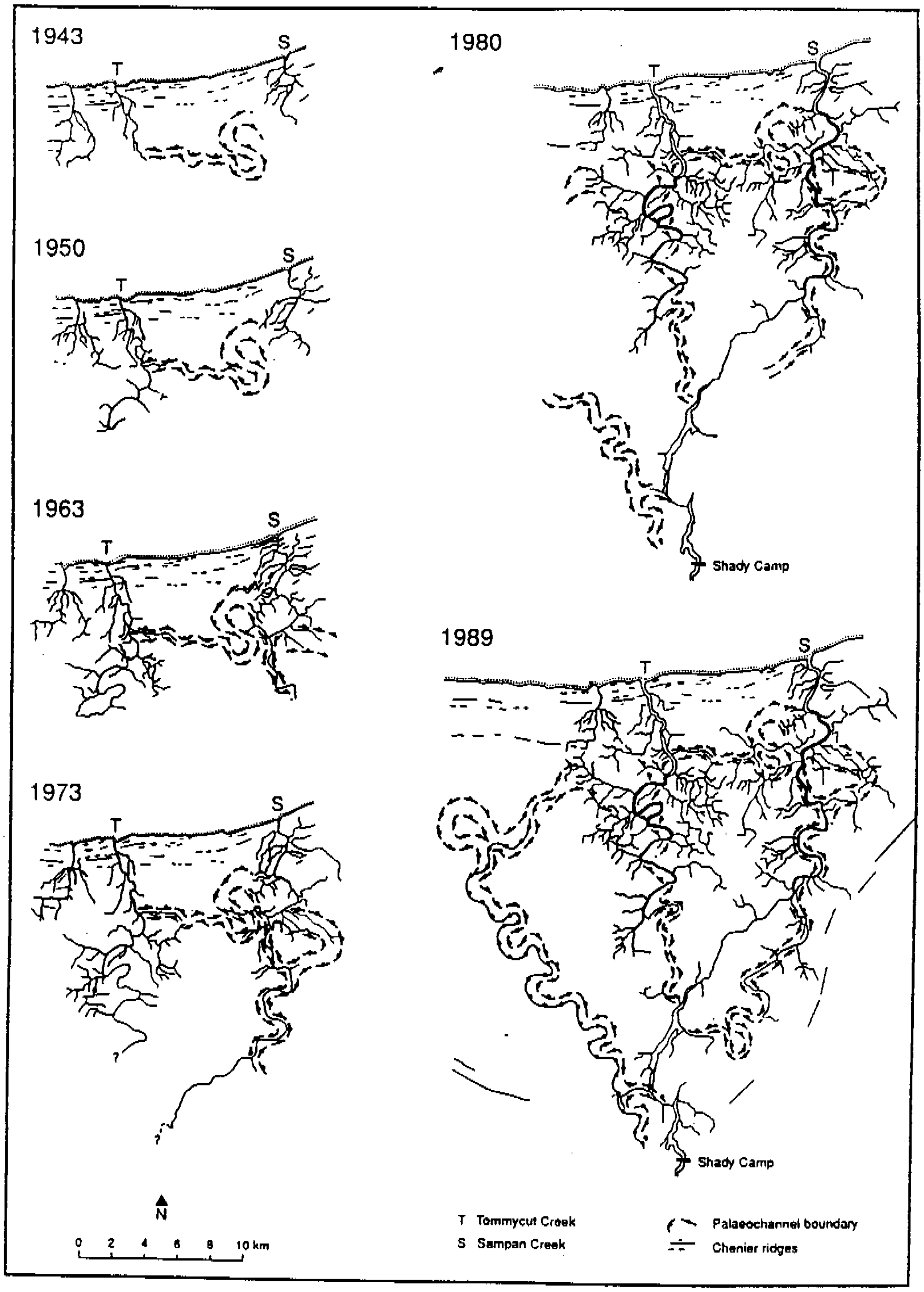

FIGURE 1.4 : Expansion of Sampan and Tommycut Creeks, Mary River, 1943 - 1989 (Knighton *et al.*, 1992).

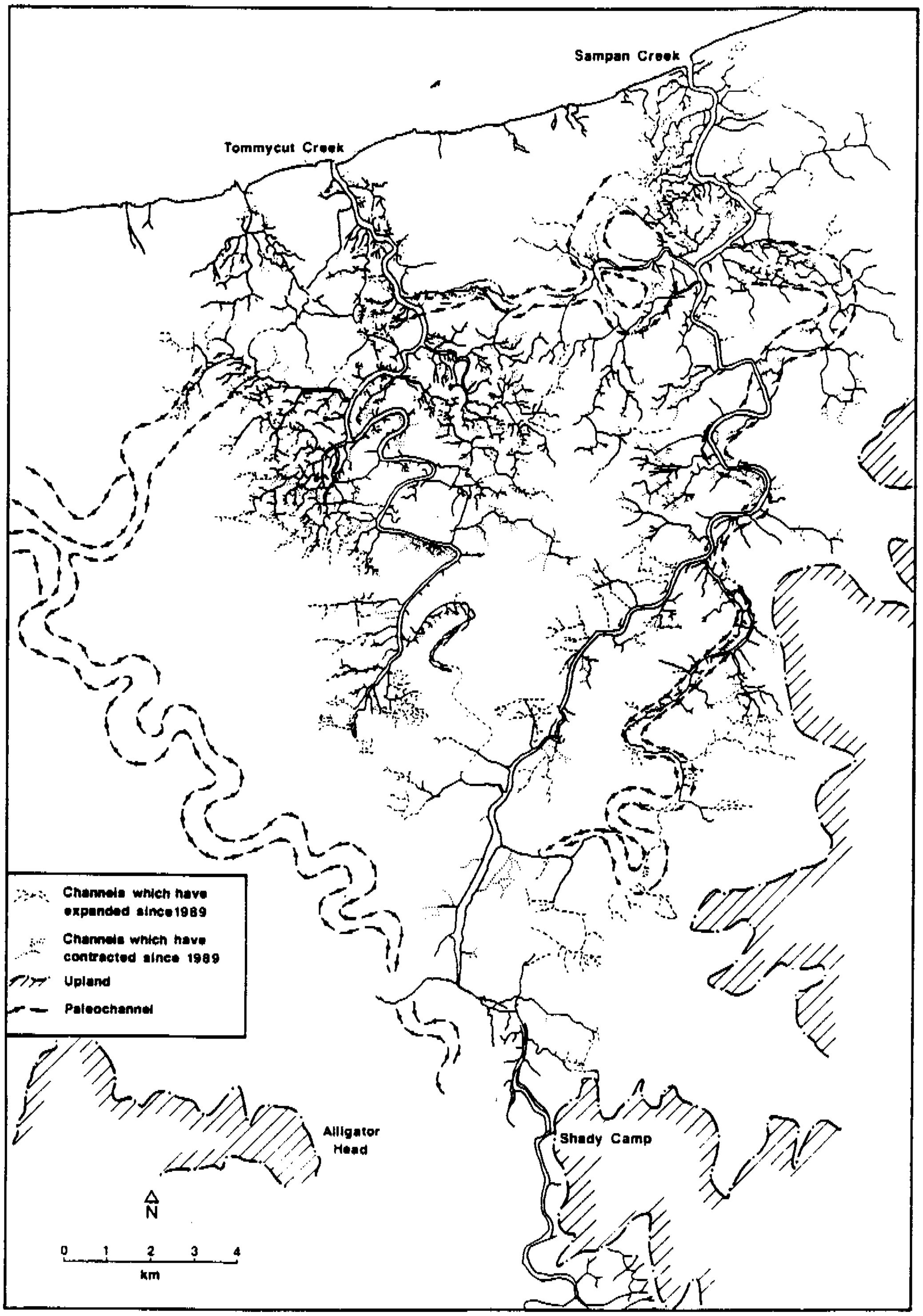

FIGURE 1.5 : Expansion of Sampan and Tommycut Creeks, Mary River, 1989-1991 (Knighton *et al.*, 1992).

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-

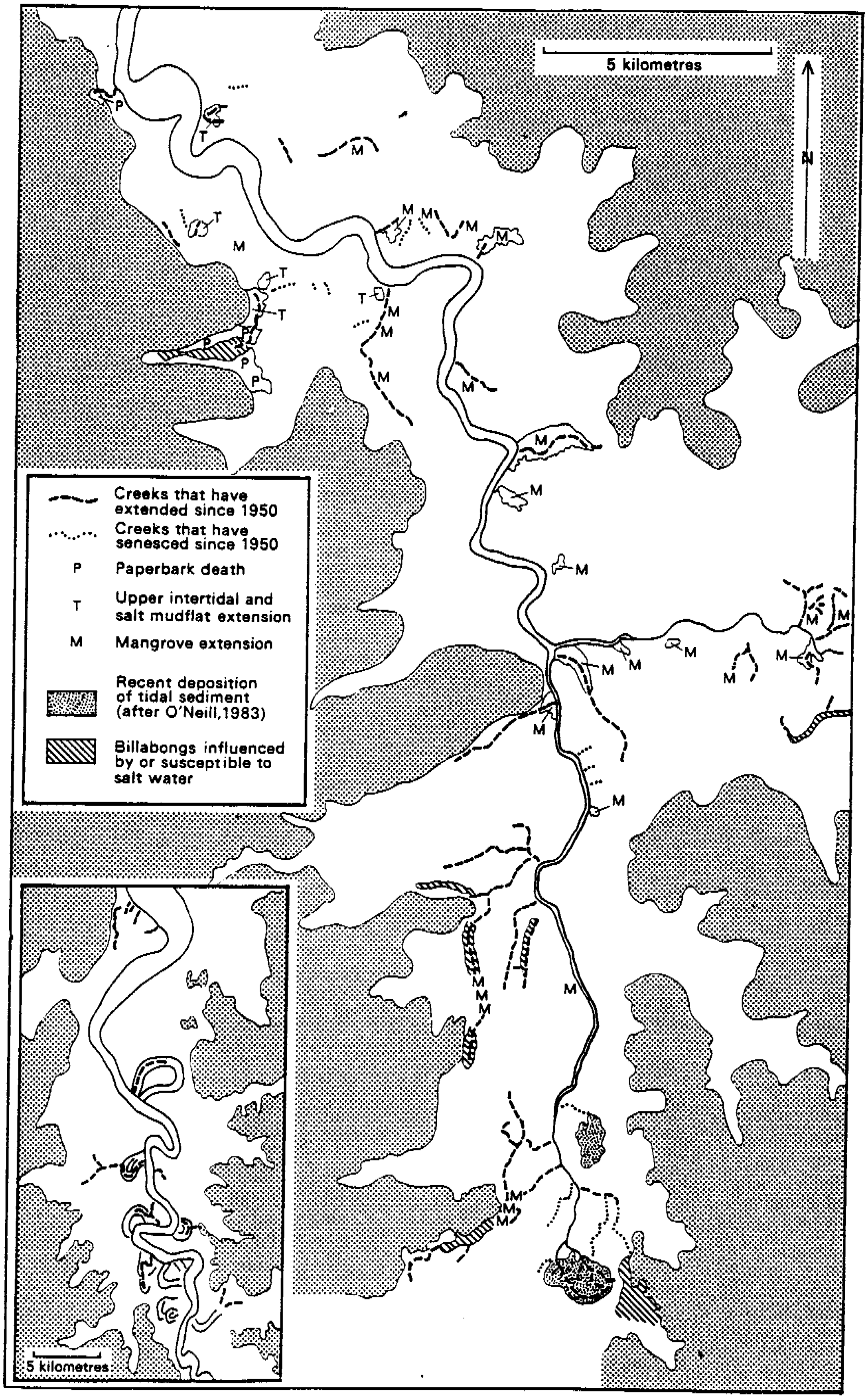

FIGURE 1.6 : Recent changes and tidal creek extension of South Alligator River, 1950 - 1983 (Woodroffe *et al.*, 1986).

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

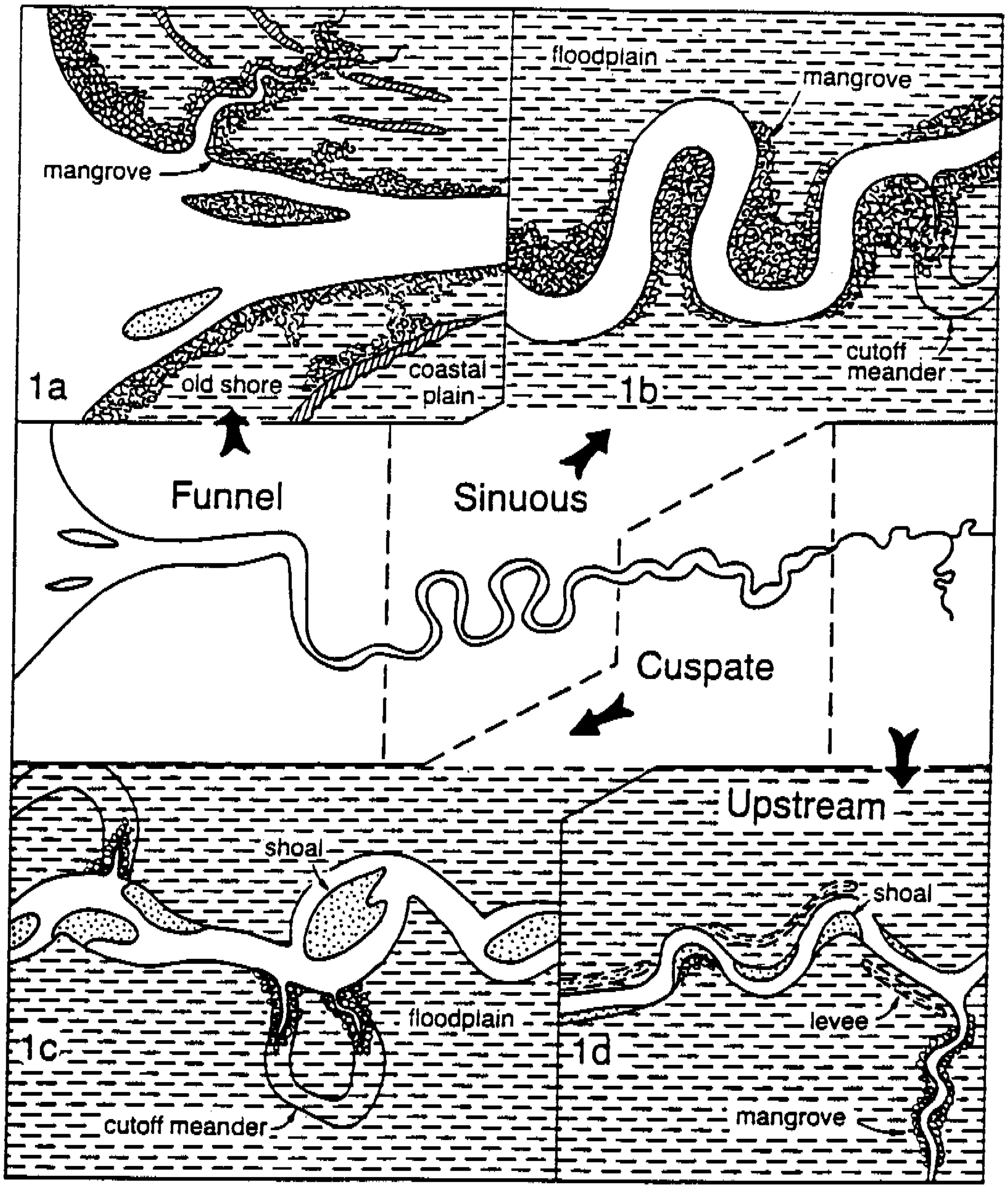

FIGURE 1.7 : Schematic tidal river showing the characteristics of different river segments (Chappell *et al.*, 1988).

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.