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Saltwater intrusion and morphological change at Point Farewell, Alligator Rivers Region

Thesis submitted in partial fulfilment of the requirement for the degree of Bachelor of Science (Honours)

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supervising scientist

Saltwater Intrusion and Morphological Change at Point Farewell, Alligator Rivers Region

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Geography Department
The University of Western Australia

eriss

Frontispiece: Photograph of Jonathon Nadji, the Traditional Owner of the Study site at Point Farewell and *Melaleuca* dieback in the background.

ABSTRACT

Since 1950 the coastal freshwater wetlands of the Alligator Rivers Region in the Northern Territory have undergone significant morphological change in response to the invasion of saltwater through the landward extension and expansion of tidal creeks. The aims of this thesis were to characterise the contemporary morphology of a small catchment at Point Farewell, a salt affected site in the Alligator Rivers Region, and to describe the recent morphological changes that have taken place since saltwater invaded the freshwater basin. Emphasis is placed on identifying the potential processes driving the morphological change, specifically oceanographic and meteorological conditions which have previously been neglected.

The research was conducted in two parts and was designed to document past and present morphological changes associated with saltwater intrusion. The contemporary morphology was mapped from the 1997 aerial photographs (scale 1:5000) and characterised following ground-truthing in 2001. Processes initiated by saltwater intrusion and currently contributing to morphological change were determined from information collated from the aerial surveys, field observations and laboratory analyses. Morphological changes that have occurred following signs of saltwater invading the freshwater basin were reconstructed from aerial photographs for the years 1950, 1975, 1984 and 1997 at a scale of 1:15,000. A series of morphological maps were then created in a GIS environment. Climatic and oceanographic data for the time span of the aerial photography were analysed to determine the conditions that promoted rapid saline intrusion and subsequent morphological change at Point Farewell.

Seven main morphological units and a number of sub-units characterise the contemporary morphology. The main morphological units identified were: (1) tidally-influenced unit; (2) upper coastal plain; (3) lower coastal plain; (4) tidal creek unit; (5) freshwater basin unit; (6) chenier unit; and (7) Koolpinyah unit. The processes of saltwater intrusion, freshwater retention and aeolian

sediment transport were observed to be currently contributing to morphological change. Saltwater intrusion through expansion of the tidal creek on the lower coastal plain has facilitated loss of vegetation and subsequent deflation of sediment following sediment desiccation in the Dry season. The lowering of the coastal plain surface by aeolian transport processes promotes favourable conditions for continuation of tidal creek development.

The catchment at Point Farewell has undergone significant morphological change since 1950. The area occupied by bare saline mudflats of the coastal plain has increased by 906%, 64% of the *Melaleuca* forest has been lost and the tidal creek has extended 4km inland. Saltwater intrusion and consequent morphological change over time appears to have been driven by climatic and oceanographic conditions experienced since 1950. The process of landward extension and expansion of the tidal creek appears to be related to the build up of threshold-exceeding events specifically Wet season floods, stronger than average monsoonal activity, storm surges and very high tides.

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CHAPTER 1: INTRODUCTION

1.1 Project Aims

Over the last 50 years, saltwater intrusion into freshwater environments through the landward extension of tidal creeks has altered the morphological characteristics of freshwater environments located within the Alligator Rivers Region, Northern Territory. The aims of this thesis are to characterise the contemporary morphology at Point Farewell, a salt-affected site in the Alligator Rivers Region, and to describe the recent morphological changes that have taken place since saltwater invaded the freshwater basin. Potential processes contributing to the recent morphological changes will be identified.

1.2 Context

Saltwater intrusion into freshwater wetlands on low-lying coastal plains of the Alligators Rivers Region has become increasingly apparent in the last 50 years (Cobb *et al.*, 2000). The dominant mechanism of saltwater intrusion is through the rapid landward extension of tidal creeks (Cobb, 1997). While it is predominantly a natural process, it is considered a major coastal management problem with respect to the preservation of freshwater wetlands and their associated flora and fauna.

The Alligator Rivers Region includes the coastal and estuarine floodplain wetlands of Kakadu National Park. These freshwater wetlands support a unique and diverse range of natural flora and fauna, a reason why they are receiving national and international acclaim (Finlayson and Von Oertzen, 1996). The coastal wetlands have a high conservation value and are an important resource for the Bininj who frequent these areas to hunt and gather food resources (Bayliss *et al.*, 1998). Hence, the process of saltwater intrusion into these valuable wetlands is of considerable concern with respect to their preservation and management.

Coastal freshwater environments have undergone significant ecological and morphological change in response to saltwater intrusion. The changes have been associated with the destruction of freshwater faunal communities in swamps and billabongs, loss of natural vegetation, encroachment of saline mudflats in formerly vegetated areas and the destruction of crocodile breeding areas (Finlayson *et al.*, 1988). The process of saltwater intrusion is not well understood and documentation of morphological change is limited. The intrusion has been attributed to natural geomorphological change (Woodroffe *et al.*, 1986), impact of feral buffalo (Fogarty, 1982) and consolidation and compaction of the coastal and estuarine plains (Woodroffe and Mulrennan, 1993). However, other processes such as oceanographic and meteorological conditions in the Van Diemen Gulf have been neglected (Bayliss *et al.*, 1998). This project aims to document morphological changes associated with saltwater intrusion, and to identify processes currently contributing to morphological change initiated by saline intrusion. This data will be valuable as a point of reference in light of predicted future climate changes and sea level rise, in which saltwater intrusion into freshwater wetlands is expected to manifest in a loss of vegetation of some wetlands and the replacement of much freshwater wetland with saline mudflat (Bayliss *et al.*, 1998).

1.3 Regional Setting

The Alligator Rivers Region is located in the Wet-Dry tropics of northern Australia, between latitudes 12^0S and 14^0S, approximately 150 km to the east of Darwin (Figure 1.1) (Finlayson and Von Oertzen, 1996). The region flanks the southeastern shore of Van Diemen Gulf and includes the catchments of the four main river systems: the large South Alligator and East Alligator Rivers and the smaller West Alligator and Wildman Rivers, and encompasses the 20 000 km^2 Kakadu National Park (Figure 1.1) (Finlayson and Von Oertzen, 1996). The wider Alligator Rivers Region encompasses the western estuarine river systems including Adelaide and Mary Rivers (Figure 1.2).

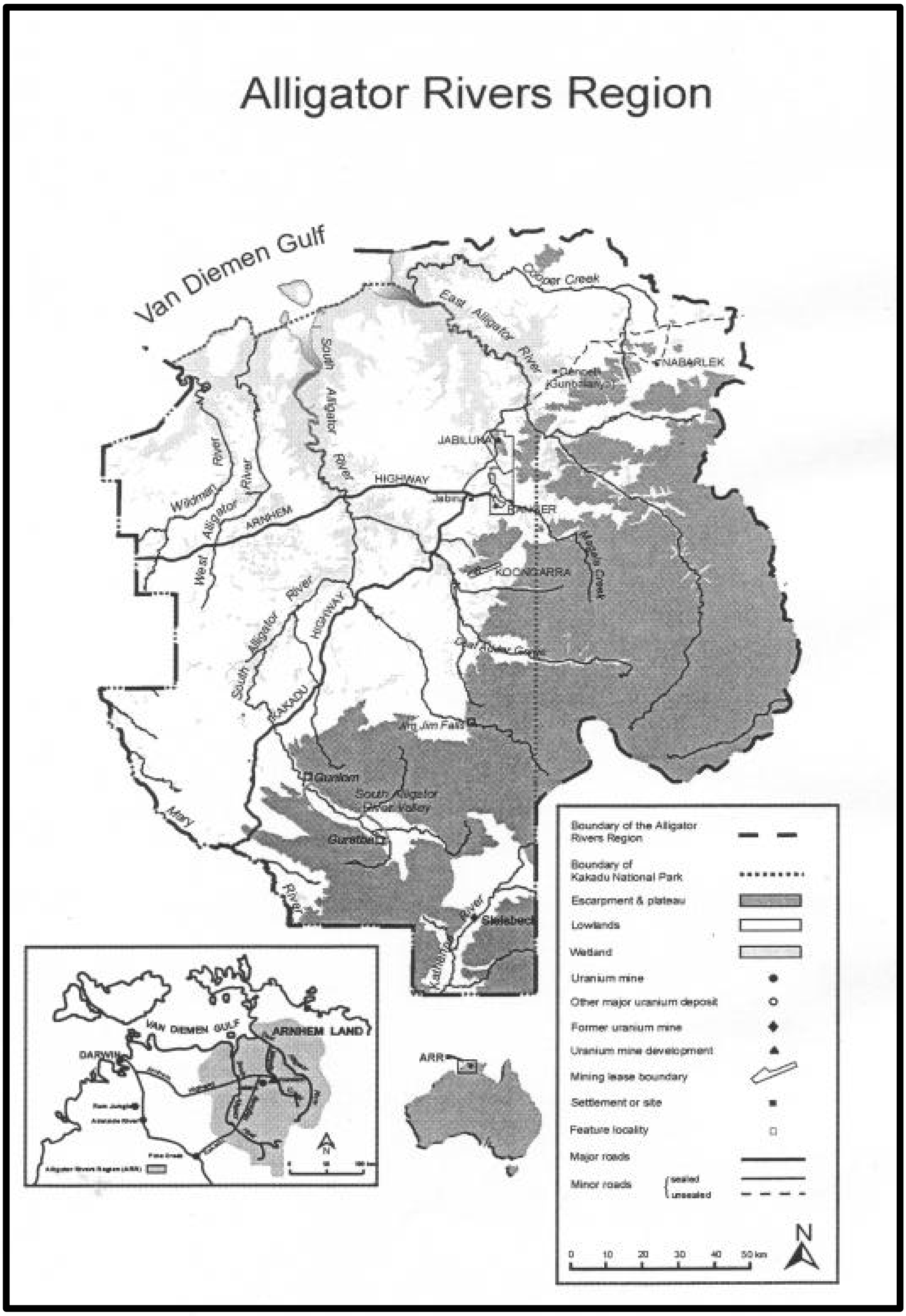

Figure 1.1 **Location of the Alligator Rivers Region**
(Source: Environmental Institute of the Supervising Scientist)

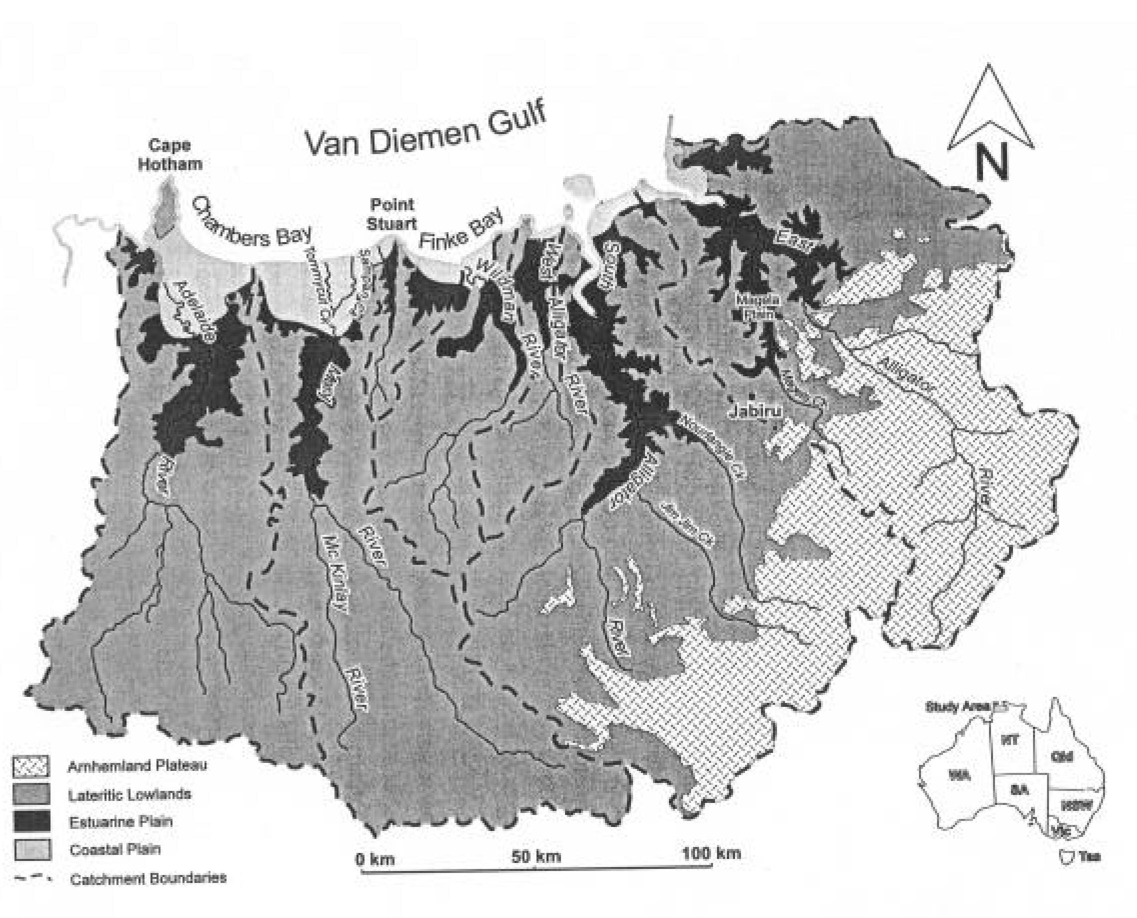

Figure 1.2 Location of the Wider Alligator Rivers Region
(Source: Bayliss *et al.*, 1998)

1.3.1 Climate

The Alligator Rivers Region is defined as lying within the Wet-Dry tropics as a result of the two distinct rainfall seasons: a “Wet” from November to March and a “Dry” from May to September (Chappell and Bardsley, 1985). The Wet season is marked by monsoonal depressions bringing heavy rain and occasional tropical cyclones, which produce torrential rain (Russell-Smith *et al.*, 1995). Hence, the rainfall regime is highly seasonal but reliable, as it does not appear to vary greatly across the season (McAlpine, 1969). The annual rainfall of the region is between 1300 mm and 1600 mm and about 92% of the mean annual rainfall falls between November and March (McQuade *et al.*, 1996).

In contrast, little rain falls during the Dry season months, and its occurrence is more variable than the wet season rainfall (McAlpine, 1969). Mean daily minimum and maximum temperatures for the Alligator Rivers Region are 19.2 ^{0}C and 30 ^{0}C in July and 25.2 ^{0}C and 31.3 ^{0}C in November at the onset of the Wet season (McAlpine, 1969). Between April and September, the winds are predominantly continental, from the south-east and east and blow offshore, while from November to February the winds are more variable, often having a strong onshore westerly and northerly component (Bureau of Meteorology, 1999).

Woodroffe and Mulrennan (1993) have suggested that the pronounced seasonality of the climate may be a significant factor contributing to the Region's vulnerability to saltwater intrusion. Intuitively, the tidal regime dominates during the Dry season hence the prolonged Dry season is conducive to the ingress of saltwater (Woodroffe and Mulrennan, 1993). Similarly, although short in duration, the Wet season is conducive to storm surge events, which have the ability to drive saltwater inland when they coincide with high spring tides (Woodroffe and Mulrennan, 1998). Hence, it is also feasible that surge events coincidental with a drier than average Wet season would also be conducive to increased saltwater intrusion. Such conditions may occur in monsoonal Wet seasons with a low incidence of tropical cyclones or drier conditions occurring in association with tropical cyclones affecting the western part of the Van Diemen Gulf.

1.3.2 Hydrodynamics

The Alligator Rivers Region is drained by a series of large macrotidal rivers that open into the Van Diemen Gulf (East, 1996). The Region stretches from Arnhemland Plateau in the south, through to low-relief river and estuarine floodplains, to a narrow coastal plain on the shore of the Van Diemen Gulf in the north (Wasson, 1992). The low-lying coastal and estuarine floodplains that flank the river systems have elevations close to spring high tides, which are approximately 6 m above the Australian Height Datum (Wasson, 1992). The high tidal range coupled with the low gradient of the floodplains enables tidal influence to penetrate over 100 km up the river systems (Woodroffe *et al.*, 1986). This is the reason why these are termed 'macrotidal' rivers.

Although the river systems are tide dominated, the flow hydrology is highly seasonal in response to the pronounced seasonality of the monsoonal rainfall regime (Woodroffe *et al.*, 1986). Freshwater discharge into the rivers is regulated by Wet season monsoonal rainfall, since at the onset of the Wet season the floodstage increases, the floodpeak rises and only minor reversions due to high freshwater discharge occur (Woodroffe *et al.*, 1986). The flood peak causes extensive flooding of adjacent low-lying floodplains predominantly from overbank wash (Woodroffe *et al.*, 1986). Estuarine reaches are predominantly fresh as during the flood events there is a significant change in the salinity levels due to freshwater inputs (Woodroffe *et al.*, 1986). Wet season rains fill the creeks and streams and cover the low-lying coastal and estuarine floodplains to a depth of several metres (Walden, 2000).

Storm surge is another significant hydrodynamic phenomenon in the Wet season. This is caused by the coincidence of low-pressure atmospheric conditions, prolonged onshore winds and wind-generated currents, and high water discharge (Woodroffe and Mulrennan, 1998). The storm surge effect aids in raising water levels within the estuarine reaches of the rivers (Woodroffe and Mulrennan, 1998). Intuitively, when storm surge coincides with high spring tides, the result is a significant temporary increase in tidal elevation, allowing tidal influence to penetrate further inland and inundating low-lying freshwater wetlands along the coastal plain (Woodroffe and Mulrennan, 1998).

A few months after the conclusion of the Wet season, freshwater runoff ceases and estuarine reaches become increasingly saline as tidal flows dominate over the floodwaters (Woodroffe *et al.*, 1986). The freshwater that inundated the low-lying floodplains and billabongs begins to evaporate, and the prolonged Dry season allows the floodplains to dry out, isolating a few permanent billabongs in deeper sections of the river channels and on the floodplains (Walden, 2000). Much of the plains dry to desiccation during the Dry season. Their surface clays crack and break, becoming sensitive to erosion (Walden, 2000).

1.3.3 Morphology of the Coastal Plain

The plains and wetlands of the river systems can be subdivided into three main morphological provinces on the basis of landform, sediment patterns and dominant processes in operation, which are mainly inferred (Woodroffe *et al.*, 1986). These are the coastal, deltaic-estuarine and alluvial provinces (Figure 1.3) (Woodroffe *et al.*, 1986). A number of morphological units are recognized within each province and these vary according to the distinct characteristics of individual river systems and their evolutionary stages of development.

Point Farewell, the area of research interest in this study, is located within the coastal plain of the East Alligator River (Figure 1.3). The main morphological units of the coastal plain at Point Farewell are consistent with those identified by Woodroffe *et al.* (1986) for the South Alligator River and by Woodroffe and Mulrennan (1993) for the Lower Mary River Plains. In general, a mangrove unit lies seaward of the coastal plain flanking the estuarine funnels and tidal creeks (Woodroffe *et al.*, 1986). This unit is flooded tidally and functions to buffer the coastal plain from erosion and severe flooding (Woodroffe *et al.*, 1986).

A saline mudflat occurs landward of the mangroves fringing the coast, as well as in isolated pockets across the plains where saltwater has intruded into previously vegetated areas (Woodroffe and Mulrennan, 1993). These areas are generally bare or vegetated with halophytic plants that can tolerate saline conditions and tidal inundation (Woodroffe and Mulrennan, 1993). Between spring tides the surface of the saline mudflats dry into polygonal cracks, and the surface often develops a crust as clay particles form silt and sand-sized aggregates (Woodroffe and Mulrennan, 1993).

Following Coleman and Wright (1971), the coastal plain can be sub-divided into upper and lower deltaic plains based on difference in elevation and hence length of Wet season inundation (Woodroffe *et al.*, 1986; Woodroffe and Mulrennan, 1993). Some parts of the lower coastal plain support stands of *Melaleuca* forest, which are localised in areas that receive freshwater runoff (Woodroffe and Mulrennan, 1993). These areas remain wet for most of the year (Woodroffe and Mulrennan, 1993).

Palaeochannels, former tidal channels, are distinct features on the coastal plain. Some channels can remain wet throughout the year. Others dry out and become saline mudflats. Both are thus susceptible to saltwater intrusion (Woodroffe and Mulrennan, 1993). Cheniers are sandy coastal ridges with shell and shell fragments overlying muddy nearshore sediments (Woodroffe *et al.*, 1986). Chenier ridges are a characteristic of the coastal plain and are a testament to the processes of overbank wash and storm surge that occur during each year (Cobb, 1997). They mark a period of interruption of the normal muddy progradation of an estuarine shore (Woodroffe *et al.*, 1986). Cheniers form a natural barrier protecting low-lying freshwater environments from tidal processes and have the ability to encapture large volumes of Wet season runoff (Woodroffe and Mulrennan, 1998).

1.4 Saltwater Intrusion in the Alligator Rivers Region

1.4.1 Process of Saltwater Intrusion

Saltwater intrusion has altered the delicate balance between freshwater and tidal regimes on the coastal and estuarine floodplains of the Alligator Rivers Region (Knighton *et al.*, 1992). As there are only small differences in elevation between salt and freshwater environments, only a slight change in estuarine water levels can cause disequilibrium (Knighton *et al.*, 1992). On the Mary River, saltwater intrusion has occurred as the direct consequence of the breakdown of barriers separating marine and freshwater environments (Knighton *et al.*, 1992; Woodroffe and Mulrennan, 1993). Since the late 1930s and early 1940s, tidal creeks have increased penetration to freshwater environments as a result of the breakdown of chenier ridges, which previously limited their inland extent (Knighton *et al.*, 1992). However, the initial cause of the breach is uncertain.

Tidal creek extension has been identified as the dominant mechanism of saltwater intrusion. Knighton *et al.* (1992) reconstructed the progress of network expansion on the Lower Mary River Plains over a period of 50 years from detailed maps drawn from aerial photographs. The tidal creek network of the region had developed through a combination of main channel extension and tributary growth (Knighton *et al.*, 1992). The general process

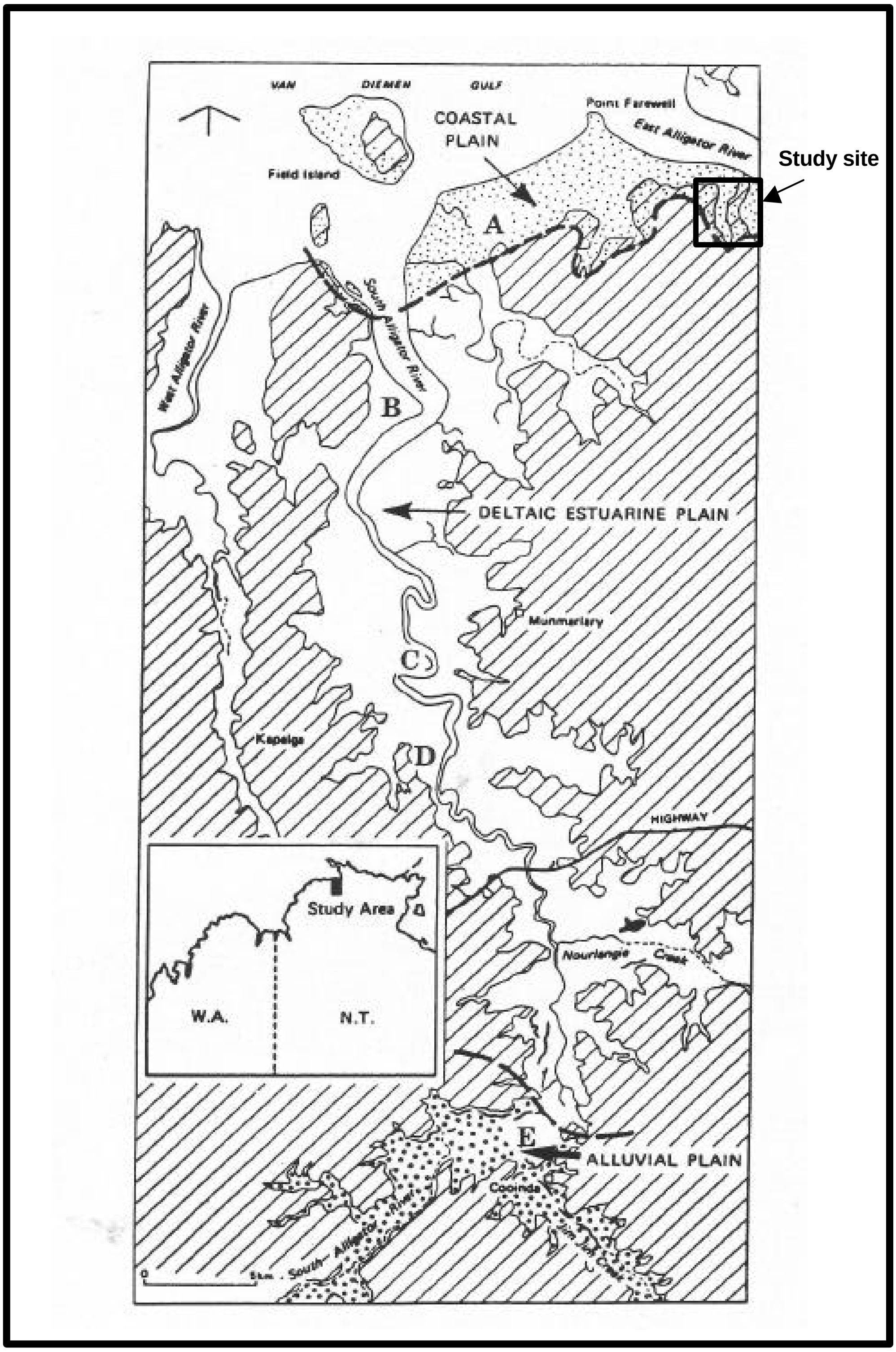

Figure 1.3 Morphological Provinces of the South Alligator River

Diagram illustrates the three morphological provinces after Woodroffe *et al.* (1985a) for the South Alligator River, the location of Point Farewell and the study site on the coastal plain. These provinces are applicable for other rivers within the Alligator Rivers Region.

(Source: Woodroffe *et al.*, 1986)

of tidal creek network development involves the initial surface invasion of saltwater during high tides along lines of slightly lower elevation (Knighton *et al.*, 1992). This leads to the formation of seepage zones, and through tidal action the central part of these are scoured (Knighton *et al.*, 1992). In turn, this increases the efficiency of drainage through the channels that then incise (Knighton *et al.*, 1992). Wet season floods may accentuate the channel incision process as tidal creeks act as efficient conduits to the sea, however tidal erosion is probably the dominant process (Knighton *et al.*, 1992).

Tidal creek networks on the Lower Mary River have grown at an exponential rate according to Knighton *et al.* (1992) and Woodroffe and Mulrennan (1993). Cobb (1997) reconstructed the progress of network development on the South, East and West Alligator Rivers using similar techniques to Knighton *et al.* (1992) and concluded that the tidal creek networks linked to those streams had experienced a linear rate of growth. Regardless of the mode of growth, the process of saltwater intrusion within the river systems has been operating at a rate not observed to occur within the freshwater counterparts.

The difference in frequency/magnitude relationships between tidal and fluvial processes is significant given the rate of saltwater intrusion. The flow in rivers is unidirectional in contrast to the bi-directional flow in tidal creeks (Knighton *et al.*, 1993). The large tidal range guarantees that rivers and creeks experience two bankfull and two lowflow discharges each day (Knighton *et al.*, 1992). Where rivers change from an estuarine funnel to a sinuous form, the peak spring tide flow can be 10 times the mean annual flood (Chappell and Woodroffe, 1985). There are few rivers worldwide that experience a flood 10 times the mean annual flood, where even the 100-year flood is usually only 2 to 4 times the mean flow regime (Heerdegen and Hill, 2000). Thus it is not surprising that freshwater systems can revert to saline environments given the magnitude and consequent geomorphic power of the tidal processes which are at times exceptionally greater than their freshwater counterparts (Knighton *et al.*, 1992; Heerdegen and Hill, 2000).

1.4.2 Morphological Evidence of Saltwater Intrusion

Documentation regarding the morphological evidence of saltwater intrusion in this area to date has been fairly general, apart from the information regarding landward extension and expansion of tidal creek networks. On the Lower Mary River Plains, saltwater intrusion into freshwater wetlands has resulted in localised scour and dieback within stands of *Melaleuca* forests (Knighton *et al.*, 1992; Woodroffe and Mulrennan, 1993). Williams (1984), Woodroffe *et al.* (1986) and Woodroffe and Mulrennan (1993) noted: (1) the expansion of salt mudflat in areas where saltwater has intruded into formerly freshwater vegetated areas; (2) *Melaleuca* species dieback; and (3) accretion of sediment on the floodplain adjacent to, and at the end of, tidal channels as evidence of saltwater intrusion on the Lower Mary, East Alligator and South Alligator River plains.

Remote sensing and Geographical Information Systems (GIS) are emerging as powerful tools for identifying, monitoring and predicting the trends of saltwater intrusion in the Alligator Rivers Region. Landsat multi-spectral scanned (MSS) and thematic map (TM) imagery has been used to quantify short and long-term land cover changes on the Mary River floodplain (Ahmad and Hill, 1995) and in identification of past and present changes in the sub-surface hydrology associated with saltwater intrusion (Jolly and Chin, 1992). Bell *et al.* (2000) used AirSAR (Airborne Polarimetric Synthetic Aperture Radar) to map soil salinity, which is a key biophysical parameter for monitoring and managing environmental changes associated with saline intrusion. Remote sensing technology offers detailed analyses on the larger scale, such as the catchment of the Lower Mary River, and even across the Alligator Rivers Region. However, small-scale studies on morphological changes associated with saltwater intrusion, such as those associated with catchments of single tidal creeks are essential to gain a more comprehensive assessment of process and trends.

1.4.3 Possible Causes of Saltwater Intrusion

Saltwater intrusion has resulted primarily from the gradual extension of tidal influences along former and existing channels, the expansion of small tidal creeks and the formation of new tidal creeks into freshwater environments (Woodroffe and Mulrennan, 1998). However, there is much debate over the mechanism responsible for saltwater intrusion and there is much uncertainty on interpreting the evidence supporting the different arguments.

The Adelaide-based National Tidal Facility has suggested a rise in sea level but no substantial evidence is provided. However, analysis of the Darwin tide record by various authors such as Harvey (1979), Aubrey and Emery (1986) and Bryant *et al.* (1988) has produced contradicting results. The analysis undertaken by the National Tidal Facility in Adelaide indicates a slight rise in sea level in contrast to Aubrey and Emery (1986) who detected a slight fall in sea level. Single, isolated storm events or surges may have occurred and contributed to the drift between the two studies given that Wet season storm surge is generally particularly pronounced in semi-enclosed basins such as the Van Diemen Gulf (Woodroffe and Mulrennan, 1993).

Although analysis of rainfall data shows no clear correlations between particularly wet monsoons and the onset of creek extension, periods of rapid tidal creek extension on the Mary River have occurred during periods of high rainfall and floodwaters (Jolly and Chin, 1992). Knighton *et al.* (1992) has acknowledged that Wet season floods accentuate the scour of tidal channels and play a similar role in channel excavation as does tidal-induced erosion. Also, Woodroffe and Mulrennan (1993) found that the headward sapping and extension of creeks in particular areas on the Lower Mary River Plains has occurred as a result of overbank flows from billabongs.

The most-favoured argument is the impact of feral buffalo. Water buffalo, *Bubalus bubalis*, were introduced into the Northern Territory during the late 1820s from Timor and nearby islands (Stocker, 1970). They were so prolific in the Alligators Rivers Region during the 1940s to 1970s that action was undertaken to control their numbers (Lindner, 1995). It was observed that water buffalo grazing and trampling along channel heads and banks resulted in the breakdown of levees, expansion of existing tidal creeks and the formation of new channels (Fogarty, 1982). Although the impact of feral buffalo may have been significant when numbers were high, unless there are significant lag effects, this argument can not be used to explain why saltwater intrusion is still presently active within the Region and why it continues to affect new areas.

Other suggestions have included the consolidation and compaction of the coastal plains, which has lowered the plains below the elevation of the high spring tides (Woodroffe and Mulrennan, 1993). However, the rate of consolidation and compaction is unknown. The natural geomorphic changes associated with the evolution of the river systems, specifically meander cutoff without meander regrowth have been linked to saltwater intrusion (Woodroffe *et al.*, 1986). Such change acts to shorten the river, allowing the tidal influence to penetrate further inland, gaining access to freshwater wetlands below the elevation of high spring tide (Woodroffe *et al.*, 1986). Meander cutoff without regrowth has occurred on the South Alligator River over the last few thousand years, a system where saltwater intrusion has been prominent (Woodroffe *et al.*, 1986).

1.5 Local Setting

The area of interest including an infilled embayment, tidal creek and chenier sequence at Point Farewell is located on the southern coastline of the East Alligator River estuarine funnel, approximately 12 km south-east of the Point Farewell salient tombolo (Figure 1.4). The study site is located within the coastal plain province of the East Alligator River. The area is a salt affected site that has been subject to saltwater intrusion since 1950.

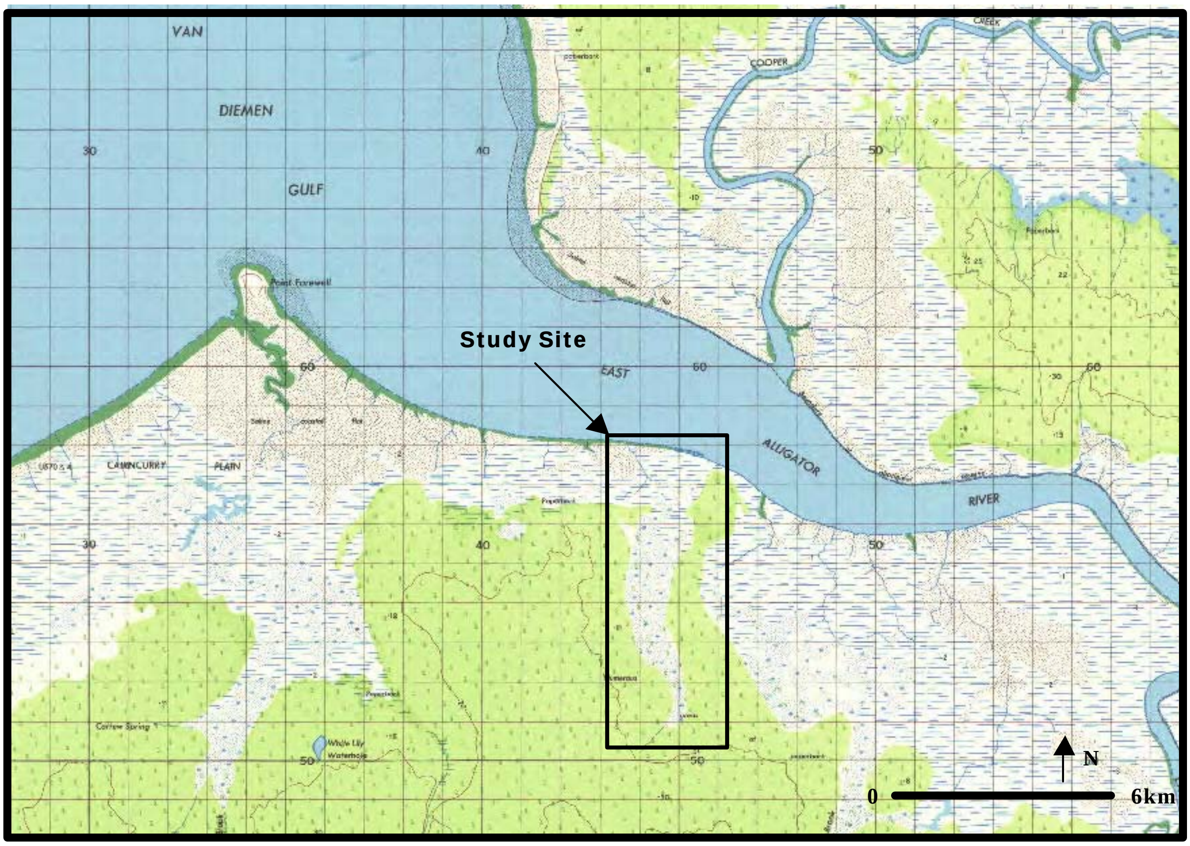

Figure 1.4 Location of Study Site

(Source: Royal Australian Survey Corps)

Cobb (1997) examined aerial photographs for the years 1950 to 1991. She noted evidence of localised rapid tidal creek extension and mangrove encroachment and attributed this to the process of saltwater intrusion. Evidence of processes such as saltwater intrusion that encompasses the study area has been revealed in the morphology. For example, a substantial amount of sediment has been removed from the floodplain over time, which has been localised within areas of *Melaleuca* forest dieback. The old ground surface level can be identified from the discolouration on old trunks of *Melaleuca* species and the exposure of their surface roots (Plate 1.1). Cracking patterns of clays on the saltflats that dry to desiccation during the Dry season becoming erosionally sensitive (Plate 1.2) illustrate the impact of climate and hydrology (Cobb, 1997; Heerdegen and Hill, 2000). Also, Cobb (1997) noted the configuration patterns of large tree logs and wooden debris scattered across the salt flats as evidence of the impact of storm surge and overwash flow on the coastal plain.

Plate 1.1 **Dead Trees at Point Farewell**
Saltwater intrusion has resulted in die back of large stands of *Melaleuca* species and localised scour within these areas indicated by root exposure. Photograph was taken east of study site.

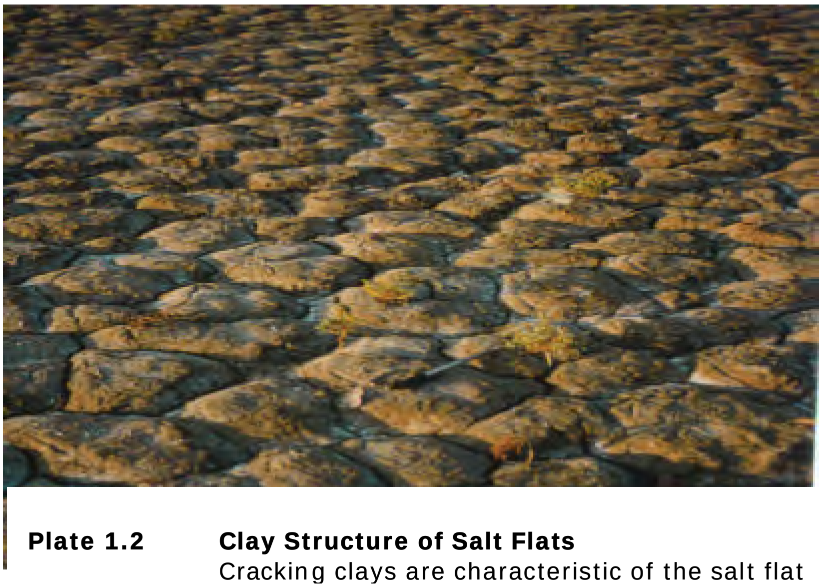

Plate 1.2 **Clay Structure of Salt Flats**
Cracking clays are characteristic of the salt flat surface at Point Farewell. The surface is smoothed from repeated overwash during wet season and desiccated during the Dry season. (Source: Cobb, 1997)

Work by Cobb (1997) and Heerdegen and Hill (2000) at Point Farewell, which includes the study site, has formed a generalized base on which to build a more detailed study. These authors have shown that the tidal creek within the study site has rapidly extended inland over the past 50 years and is evidence of saltwater intrusion. However, documentation of morphological changes associated with saltwater intrusion is limited. This thesis will extend previous work done by the above authors, and offer a detailed account of the past and present morphological changes associated with saltwater intrusion.

1.6 Project Significance

The study site at Point Farewell has been selected as a good case study to assess the impact of saltwater intrusion for several reasons. First, the majority of the research to date has been focused at the scale of the entire catchment of the Lower Mary River Plains (Jolly and Chin, 1992; Knighton *et al.*, 1992; Woodroffe and Mulrennan, 1993; Ahmad and Hill, 1995) and within the morphological provinces of the East, South and West Alligator Rivers (Cobb, 1997; Cobb *et al.*, 2000). The current research is focused on a smaller scale, first order stream and floodplain approach, which will offer a more detailed assessment that may also serve as an analogue for larger scale processes.

Second, the site is of cultural significance to the Bunitj clan who are the traditional owners of the coastal lowlands of the East Alligator River. Jonathon Nadji, the traditional owner of the study site, raised his concern to the Environmental Institute of the Supervising Scientist in 1995 regarding the tidal creek extension, *Melaleuca* (Gungod or Kunkod) dieback and the disappearance of magpie geese (*Anseranus semipalmata*) (Nadji pers. comm). Also, the area is fed by freshwater springs, which in the past served as a valuable source of freshwater during the Dry season when members of the Bunitj clan frequented the area (Nadji pers. comm).

Thirdly, this research has implications for management of saltwater intrusion. Acting out of his concern, Jonathon Nadji constructed a barrage across the tidal creek in 1995, to prevent further penetration of saline water and promote freshwater retention within the basin (Nadji pers. comm). Barrages are physical barriers built across streams and tidal creeks and have been the local response to saltwater intrusion but with rather limited success (Applegate, 1999; Heerdegen and Hill, 2000). This research will offer insight into the effectiveness of the barrage at Point Farewell in managing saltwater intrusion at the study site. Finally, this research will provide a baseline study for more detailed monitoring.

1.7 Statement of Objectives

In order to fulfill the aims of this research, five main objectives are required to document and characterise both past and present morphological changes associated with saltwater intrusion at Point Farewell. These are to:

1. Identify and characterise the main morphological units at Point Farewell including aspects of relief, sediment characteristics, vegetation and geomorphic processes;
2. Determine the current extent of saltwater intrusion within the freshwater basin;
3. Map and describe the morphological changes that have taken place since saltwater invaded the freshwater basin from aerial photographs (1950, 1975, 1984 and 1997);
4. Interpret morphological change over time in conjunction with climatic and oceanographic data; and
5. Identify the potential processes contributing to morphological change over time.

CHAPTER 2: RESEARCH METHODOLOGY

2.1 Research Design

The research was conducted in two parts and was designed to document morphological changes that have occurred following signs of saltwater invading the freshwater basin (Figure 2.1). The first component involved the characterisation of the contemporary morphological units. The main morphological units were identified from a base map constructed from the most recent set of aerial photographs (year 1997). This was a precursor that enabled determination of an effective sampling design for a critical evaluation of the study site. Several field investigations were employed to ground-truth each morphological unit, which involved collection of both surface sediment and vegetation samples, and documentation of areas of apparent erosion and/or deposition. Also, processes other than saltwater intrusion that were currently active within each unit were identified.

The second component involved the historical interpretation of morphological change. Interpretation of aerial photographs and GIS techniques were employed to map morphological changes following the years 1950, 1975, 1984 and until 1997. The patterns present at each time period were then analysed in conjunction with climatic and oceanographic datasets for the years 1950 to 2000 to assist in identifying the potential processes driving them.

2.2 Characterising Contemporary Morphological Units

One of the central aims of the research is to describe the surface morphology of an area that has been subject to saltwater intrusion. Morphological unit identification and classification in this thesis is based on physical characteristics of the land surface in relation to processes active within the area. The criteria for unit selection included aspects of:

Relief (height and exposure)
Sediment characteristics (colour, texture and composition)
Vegetation (community composition and cover); and

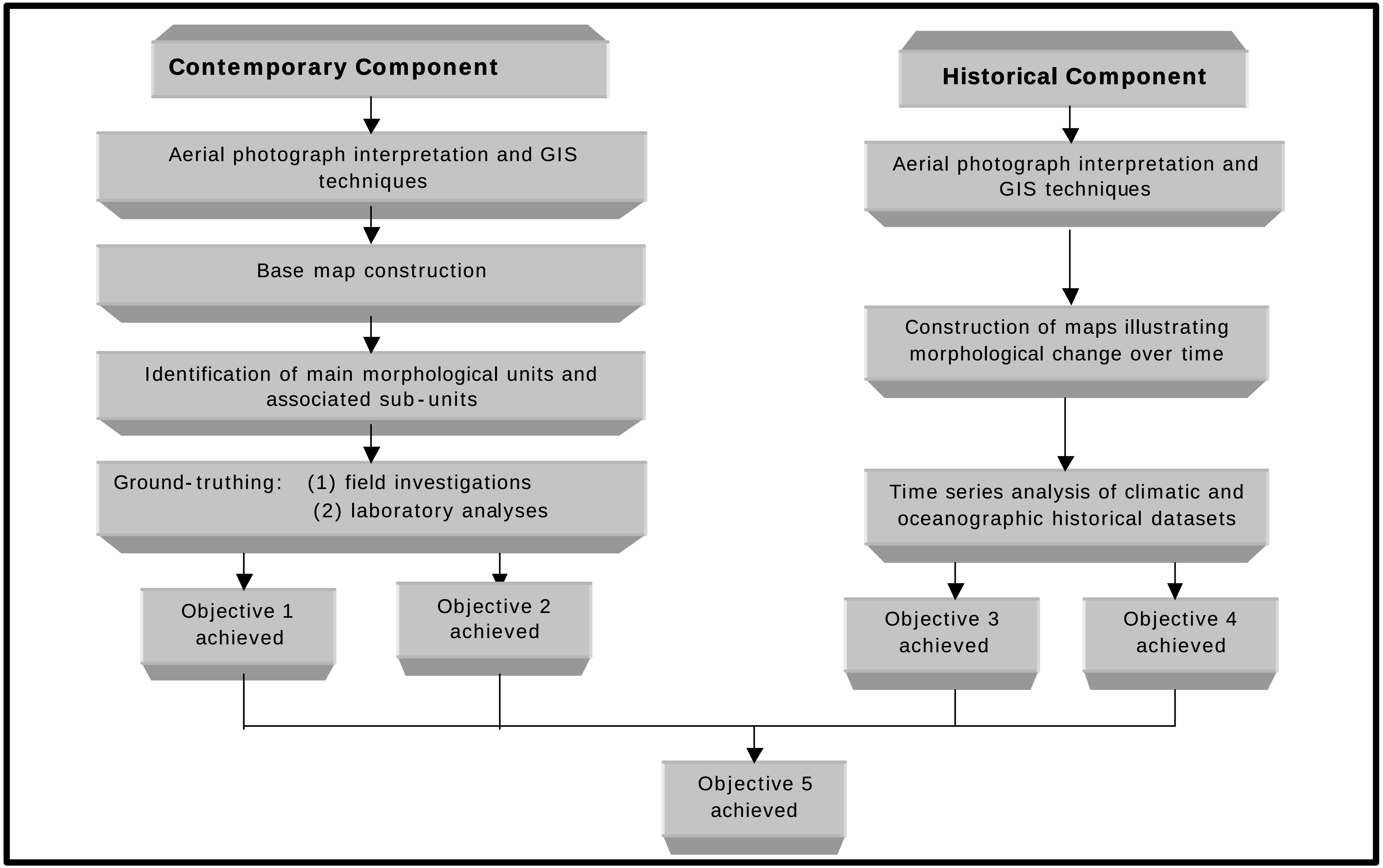

Figure 2.1 Research Design
Flow diagram summarising the two main components involved and the techniques involved in achieving each objective.

Processes (marine and fluvial).

To account for the heterogeneity within each morphological unit, sub-units were identified using the above criteria. The main morphological units and their sub-units are listed in Table 2.1.

2.2.1 Aerial Photograph Interpretation

The main morphological units were identified from aerial photographs, 1997 scale 1:5000 using a stereoscope. The colour and textural information contained within this set of aerial photographs provided a basis to discriminate and map the morphological units (Table 2.1). A morphological map was then constructed within a GIS environment to determine an effective sampling design for field investigations. The sampling design was based on the 1997 aerial photographs and ground-truthed in 2001. To account for the changes that had occurred since 1997, the unit boundaries and sampling design were reassessed after a reconnaissance trip to Point Farewell in July, 2001.

Table 2.1 **Morphological Units**
Main morphological units and sub-units identified from 1997 aerial photographs.

Morphological Unit	Sub-units
Tidally-influenced	Intertidal zone Storm surge ridge
Upper Coastal Plain	Vegetated mudflat Unvegetated saline mudflat
Lower Coastal Plain	Vegetated saline mudflat Unvegetated saline mudflat
Tidal Creek	Developing tidal creek Tidal fan Tidal splay
Freshwater Basin	*Melaleuca* forest Floodplain
Chenier	Chenier ridges
Koolpinyah	Koolpinyah surface with open woodland

2.2.2 Field Survey Techniques

Several field investigations were undertaken over a total period of three days during July and August in the 2001 Dry season. The aims of the field investigations were to (1) document the morphological features of each unit and associated sub-units and (2) collect representative sediment and vegetation samples for more detailed classification.

Field investigations were made extremely difficult due to several factors. First, the basin was completely flooded which prevented detailed ground truthing within this unit due to limited vehicle access. Consequently, site access was by helicopter, which was expensive and limited the time available in the field. The dangers encountered in the field (crocodiles!) limited the time spent within some units, such as the tidal creek and freshwater basin. However, ground- truthing was deemed sufficient for unit classification.

2.2.2.1 Field Observations

Due to difficulties encountered in the field, the processes active within each unit could not be directly measured and were inferred. For example, only visual approximations of changes in elevation were possible. An extension of this study could involve a more detailed program of fieldwork conducted over a longer period to enable more accurate declination of the units. Hence, this project is best regarded as a preliminary survey. Also, detailed field mapping using a differential Global Positioning System (dGPS) to accurately record unit boundaries was not possible. This prevented the collection of tic points to geo-reference the aerial photographs to real world co-ordinates. In turn, documentation of features and processes were qualitative and limited to observations recorded with a digital camera and video footage shot from the helicopter.

2.2.2.2 Sediment Sampling Design and Collection

A stratified random sampling design was used to collect surface sediment samples within each unit, including representatives of associated sub-units. A total of three to eight sediment samples were collected from each unit.

The number of samples varied according to the number of sub-units present. The location and number of samples taken is illustrated in Figure 2.2. Although the map is not geo-referenced in real-world co-ordinates, a hand-held GPS was used to record sample locations. The intertidal and Koolpinyah units were not sampled. Although given more time and resources more samples could have been collected, the sampling design and sediment collection was considered adequate to offer new insight into characteristics of the morphological units present.

2.2.2.3 Vegetation Surveys

Vegetation samples were collected from each unit and associated sub-units for community and species identification. Due to logistical limitations in the field, samples were only collected within localised areas of each unit and sub-units. Hence, not all species were accounted for. Vegetation samples collected were identified to species level using taxonomic keys (Wightman, 1983) and species descriptions (Brock, 1993). Recent classifications of vegetation communities within Kakadu National Park by Schodde *et al.* (1987) and Brocklehurst (1991) were used as a guide to identify communities present within the unsampled units.

2.2.3 Laboratory Techniques For Sediment Analysis

2.2.3.1 Colour and Texture

Surface sediment samples were characterised in terms of sediment colour and texture classes. Theoretically, these are both field-based sediment classification processes but they were undertaken in the laboratory due to time constraints in the field. Munsell (1954) soil colour charts were used to determine the colour of dampened sediment samples, under natural light. Field soil texture classes (after Northcote, 1979) were used to determine the following properties of each sample: texture class, coherence, bolus characteristics and ribbon length (mm). Sediment texture can give a great deal of information about sediment properties and expected behaviour. Northcote's (1979) Australian soil classification was found to be a rapid and effective way to approximate the grain size distribution of sediment samples.

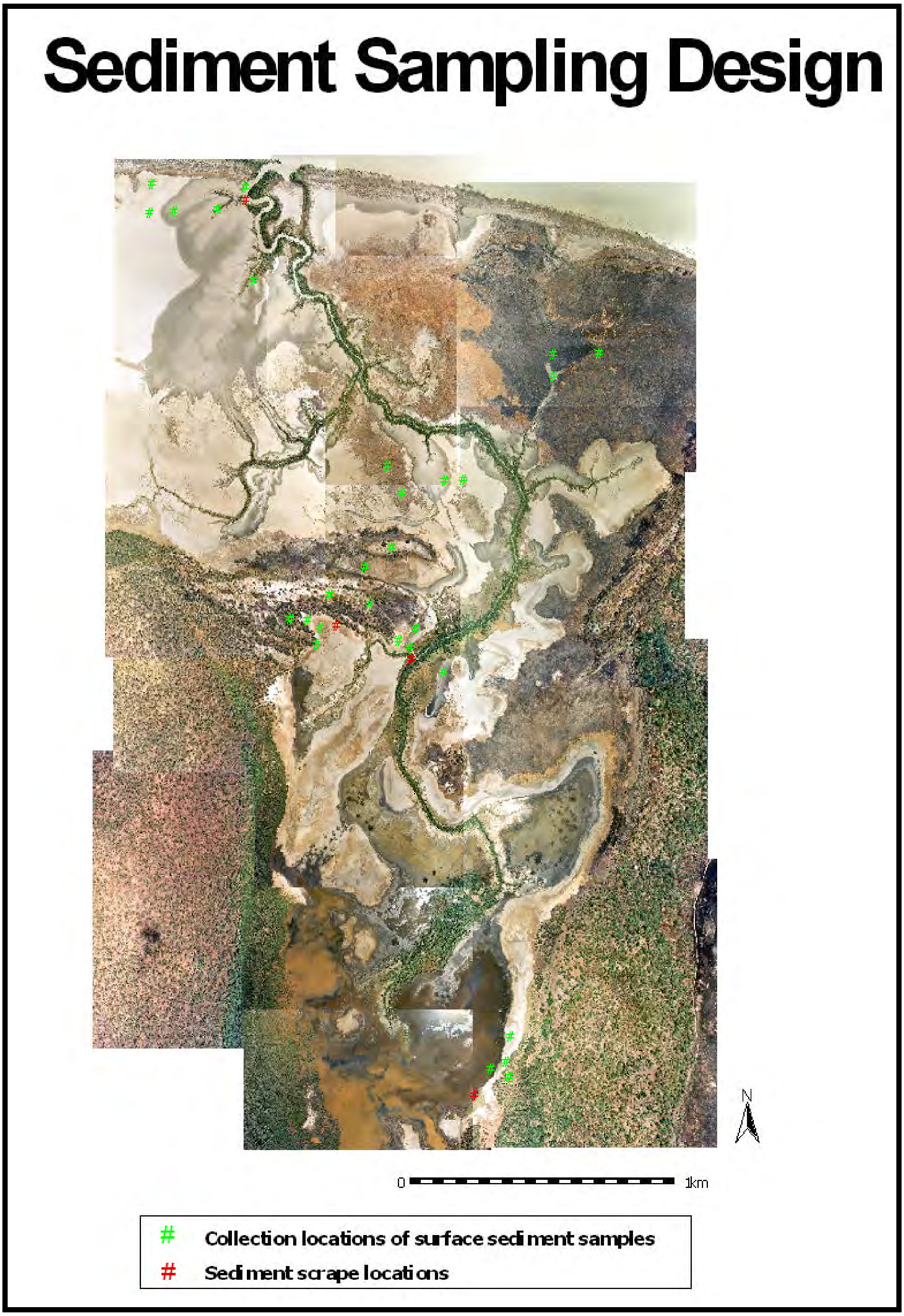

Figure 2.2 **Sediment Sampling Design**

The locations where the surface sediment samples were collected are represented by a green #. A red # represents the sites where sediment surface scrapes were taken for the ^{228}Th-^{232}Th isotope analysis.

(Source: Aerial photographs were obtained from the Environmental Research Institute of the Supervising Scientist.)

2.2.3.2 Moisture Content and Weight Loss on Ignition

Moisture content and organic content were determined for all sediment samples. Moisture content was determined from wet and oven-dried weights of sediments samples (following Rayment and Higginson, 1992), while organic content was determined by weight loss on ignition in a muffle furnace at 500^{o}C (following Rayment and Higginson, 1992).

2.2.3.3 Electrical Conductivity

Soil electrical conductivity was determined for all soil samples collected in the field. The electrical conductivity of a 1:5 soil water extract was used to estimate the soluble salt concentration in the sediment samples (following Rayment and Higginson, 1992). Electrical conductivity, range 0mS/cm – 20 mS/cm and 20mS/cm – 200mS/cm, were measured on the 1:5 soil water suspensions (following Rayment and Higgison, 1992).

2.2.3.4 Grain Size Distribution

Dry sieving and the hydrometer method were used to determine the sand, silt and clay composition of sediment samples (following Gee and Bauder, 1986). Samples comprised solely of sand were placed through a set of 0.25ϕ standard sieves, with a range of mesh sizes of -1ϕ to 4ϕ, and dry sieved to classify the size classes according to Wentworth (1922). Both techniques were used to determine the grain size distribution of samples that were comprised of sand, silt and clay. The hydrometer method was performed first, to determine the silt and clay percentages, followed by dry sieving to determine the percentage of sand.

Analysis was complicated by the presence of salt and organic content in the sediment samples. Prior to commencement of the hydrometer method, salts were washed from the samples until below 1% of their initial conductivity, to avoid flocculation. Also, samples with weight loss on ignition values greater than 2% were treated with hydrogen peroxide over a period of two weeks to remove organic matter. After removal of salts and most organic content, the hydrometer method was then commenced.

Samples were dispersed in 100mL of 5% Calgon, mixed in a mixer and then transferred to measuring cylinders and made up to 1000mL with deionised water. Hydrometer readings were taken at elapsed times of 1, 2, 3, 4, 8, 30 minutes and then 1, 2, 4, 8, 16, 29, 48, 52, 96 and 192 hours, before the experiment ceased. The grain size diameter (mm) and percent finer (%) were then calculated from a series of equations (Gee and Bauder, 1986). The sand present was then dried and placed through the set of 0.25ϕ standard sieves, with a range of -1ϕ to 4ϕ, and dry sieved to classify the size classes according to Wentworth (1922). Pointstar software (Sieve graph program) was used to illustrate the grain size distribution of each sample and to graphically determine the percentage of sand, silt and clay according to Wentworth (1922).

2.3 Determining The Current Extent Of Saltwater Intrusion

During the reconnaissance trip to Point Farewell, the tidal creek was observed to be outflanking the barrage and extending into the freshwater basin (Plate 2.1). This indicated that saltwater may be currently invading the freshwater basin. Hence it was appropriate to collect water samples at the points indicated in Figure 2.2. Although the water samples collected from the basin were predominantly fresh water, these readings are not necessarily indicative of the absence of saltwater because samples would be variable and dependant on the intensity and duration of each season and on the tide cycle. To offer an unbiased assessment, the thorium-228/thorium-232 ratio was employed to determine whether saltwater has been intruding into the freshwater basin over the last five years.

2.3.1 ^{228}Th-^{232}Th Isotope Analysis

Thorium-228 (^{228}Th) (half-life 1.9 years) is a member of the ^{232}Th decay series (Figure 2.3). The ^{228}Th concentration of freshwater sediments undergoes *in situ* changes over a period of years after saltwater has been introduced into the freshwater environment, such as through landward extension of tidal creeks. These changes occur as a result of radium (Ra) desorption and lead to the development of low $^{228}Th/^{232}Th$ activity ratios in the sediment.

Thorium-series nuclides of freshwater sediments are generally close to secular equilibrium assuming no source mixing, with $^{228}Th/^{232}Th$ activity ratio close to one. Radium is readily mobile in saline environments and is rapidly desorbed from the sediment surface after encountering saline conditions. It is then removed from the freshwater system via tidal processes. As the activity of ^{228}Th is partially supported by ^{228}Ra, saltwater intrusion will lead to a lower $^{228}Th/^{232}Th$ activity ratio of freshwater sediments. Hence, if saltwater has been intruding into the freshwater basin since barrage construction in 1995, then the $^{228}Th/^{232}Th$ activity ratios of freshwater sediments should be low (Hancock, 1996).

Sediment samples were collected along the length of the tidal creek and freshwater basin, using a 0.5cm scrape (Plate 2.2). Sediment scrapes were taken along a north to south transect, to aid in determination of the extent of saltwater intrusion in the freshwater. On return from the field, sediment scrapes were oven-dried and converted into fine homogenous powder before casting with resin into moulds (Marten, 1992). After storage of approximately 24 days to achieve radioactive equilibrium between Radium, Radon and Radon daughters, ^{228}Th and ^{232}Th concentrations will be determined by gamma spectrometry (following Marten, 1992). Although more accurate, alpha spectrometry was deemed too time-consuming for this pilot study. Also, radioactive activities should be high enough for gamma spectrometry in the samples. Unfortunately the results are not available for this thesis but will be used by the Environmental Institute of the Supervising Scientist in future research.

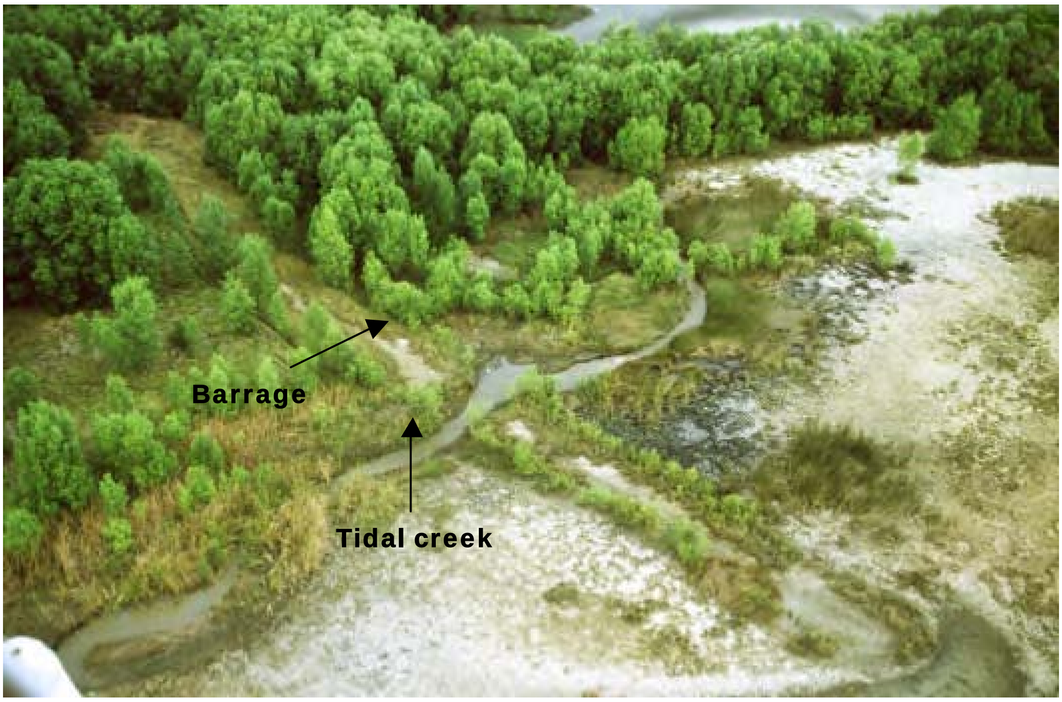

Plate 2.1 **Tidal Creek Outflanking Barrage**
Tidal creek is currently outflanking the barrage and extending into the freshwater basin, evidence of saltwater intrusion.

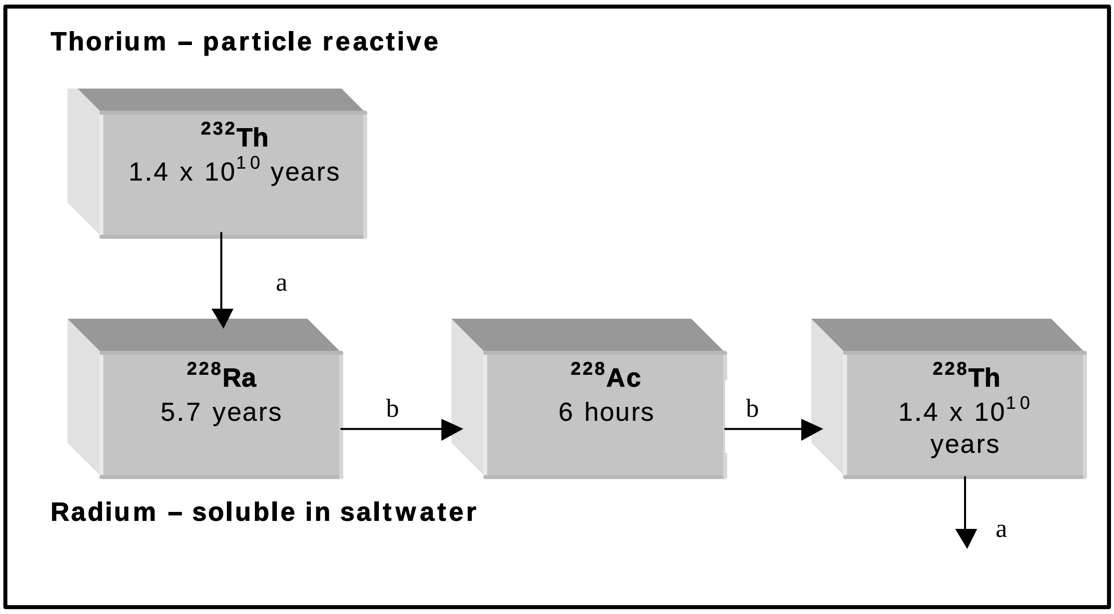

Figure 2.3 **Members of the Thorium Decay Series**
Flow diagram summaries the first few member of the thorium decay series, indicating the half-life of each member and type of decay.
(Source: after Hancock, 1996)

Plate 2.2 Sediment Scrape
A 0.5cm sediment scrape was used to collect sediment samples for the ^{228}Th-^{232}Th isotope analysis.

2.4 Reconstructing Morphological Change, 1950-1997

2.4.1 Aerial Photograph Interpretation

The morphological changes that have occurred since saltwater invaded the freshwater basin were identified from aerial photographs, for the years 1950, 1975, 1984 and 1997. The aerial photographs were flown during the Dry season of each year. This aided in determination of the landward extent of tidal creek development and the identification of morphological changes occurring within the near vicinity. However, morphological changes occurring within the basin were difficult to identify for the years 1950 and 1975 as the basin was still in flood. Although the photographs were seasonally consistent, they varied in scale and quality (Table 2.2). This posed the challenge of ensuring comparability between dates. The problem of variation in scale was overcome through the employment of GIS.

Table 2.2 Details of Aerial Photography

Date of Photography	Number of Photographs	Scale	Colour	Quality	Source
May 1950	2	1:25,000	Black & White	3	*eriss*
July 1975	2	1:12,500	Colour	2	PAN
August 1984	2	1:12,500	Colour	2	PAN
October 1997	14	1:5000	Colour	1	*eriss*

* Quality is defined on an arbitrary scale according to the ease at which the morphological changes could be identified, where 1 is the easiest.

eriss = Environmental Research Institute of the Supervising Scientist
PAN = Parks Australia North

2.4.2 *GIS Methodology and Mapping Morphological Change*

GIS was a valuable tool for registering the aerial photographs to the same working scale. The 1997 aerial photographs of scale 1:5000, offered the most detail for identification of morphological change. A mosaic of the fourteen scanned aerial photographs that spanned the study site was created within the GIS environment using Arc View and Arc Info software packages. This mosaic formed the base image to geo-reference the photographs from earlier dates. Due to a lack of common features between 1950 and 1997, image registration was sequential. The 1984 photographs were registered to 1997, then 1975 to 1984 and finally 1950 to 1975. A detailed account on the GIS methods can be found in Appendix A.

A series of morphological maps for each year was created in Arc View by digitizing the boundaries of the units and associated sub-units to illustrate the morphological changes that have occurred since 1950. Only qualitative estimates of change could be determined as percentages, as the aerial photographs were not geo-referenced in real world co-ordinates. The features used to identify the main morphological units from each set of aerial photographs are summarised in Table 2.3. This ensured that unit identification and description was both consistent and comparable for each year.

2.4.3 Climatic and Oceanographic Analysis

To assist in describing the potential processes driving the morphological changes identified, climate and oceanographic data were obtained from the Bureau of Meteorology and the National Tidal Facility for the time span of 1950-2001. This data consisted of monthly rainfall for Oenpelli (Figure 1.1), mean monthly-observed water levels for Darwin and cyclonic activity for the Northern Territory. Although Darwin is located outside the Van Diemen Gulf, this data was the best available given there are no permanent tide gauges in the Van Diemen Gulf waters.

Annual Wet season rainfall, for the months of November to March was extracted from the raw dataset. The mean Wet season rainfall was calculated for the years 1950-1997 to normalise the data in order to determine which years experienced above or below Wet season rainfall. Mean monthly water levels for Darwin were also normalized for the years 1966-1997. Morphological changes identified in the aerial photography were analysed in conjunction with the normalized climatic and oceanographic datasets to assist in identification of the potential processes driving them.

Table 2.3 **Criteria for Morphological Map Construction**
Features used to identify morphological units and associated sub-units from aerial photographs when viewed under a stereoscope .

UNIT	SUBUNIT	FEATURES
Tidally-influenced	Intertidal zone	Mangroves lining estuarine funnel
	Natural levee banks	Raised river banks running parallel to estuarine funnel; vegetated or bare
	Storm surge ridge	Area of build -up running perpendicular to the coastline
Upper Coastal Plain (Eastern side of tidal creek)	Vegetated mudflat	Landward of the tidally-influenced unit, lying at a higher elevation than the lower coastal plain with mudflat surface vegetated by grasses and sedges
	Unvegetated saline mudflat	Landward of the tidally-influenced unit, lying at a higher elevation than the lower coastal plain, mudflat surface bare of vegetation and is found adjacent to the tidal creek or developing tidal creek tributaries
Lower Coastal Plain (Western side of tidal creek)	Vegetated saline mudflat	Landward of the tidally-influenced unit, lying at a lower elevation than the upper coastal plain with mudflat surface vegetated with sedges and grasses
	Unvegetated saline mudflat	Landward of the tidally-influenced unit, lying at a lower elevation than the upper coastal plain with mudflat surface bare of vegetation and is found adjacent to the tidal creek or developing tidal creek tributaries
Tidal Creek	Tidal creek	Mangroves flanking tidal creek
	Developing tidal creek	Distinct tidal channel extending landward of the main tidal creek but not stabilized by mangroves
	Tidal fan	Distributary channels of developing tidal creek network, splaying tidal flows at their heads in the shape of a fan
	Tidal splay	Splay of recent tidal flow issued from the distributary channels of the developing tidal creek network; tidal extent represented by a darker surface, which is characteristic of recent inundation
Palaeocoastal Plain	Palaeochannels	Former tidal channels located on the coastal plain, which are not connected to the present network
Freshwater Basin	Freshwater basin	Depression holding water, confined by the Koolpinyah surface
	Melaleuca forest	*Melaleuca* species inhabiting the freshwater basin
	Floodplain	Low -lying plain surrounding the freshwater basin either vegetated or bare
Chenier	Chenier ridges	A sequence of sand ridges separating the coastal plain from freshwater basin; vegetated or bare
Koolpinyah	Koolpinyah surface with open woodland	Elevated surface vegetated by open woodland that confines the freshwater basin

CHAPTER 3: CONTEMPORARY MORPHOLOGY AT POINT FAREWELL

3.1 Organisation of Results

The contemporary morphology at Point Farewell was described from 1997 (scale 1:5000) aerial photographs and field investigations in 2001. Information collated from the aerial surveys, field observations and laboratory analyses was combined in characterising the units and to provide morphological evidence of localised processes, such as saltwater intrusion. A morphological map was constructed illustrating the main morphological units and their associated sub-units.

3.2 Morphological Units

The study site at Point Farewell (Figure 3.1) consists of a single tidal creek extending landward across the coastal plain into the freshwater basin. The freshwater basin is bordered by a relatively level floodplain and confined by a sequence of chenier ridges and the Koolpinyah surface. Within the study area, seven main morphological units and a number of morphological sub-units are recognized (Figure 3.2). Unit descriptions are similar to classifications by Woodroffe *et al.* (1986) and Woodroffe and Mulrennan (1993), however there is some deviation given the focus of the study. Although the study area is located within the coastal plain province of the East Alligator River, the site has counterparts amongst the deltaic-estuarine province. Hence, some unit descriptions and location of boundaries differ from previous research.

The main morphological units and associated sub-units are summarised in Table 3.1 and are described below. Each unit is characterised by its sediment characteristics, vegetation, inundation and processes currently active, which are inferred. A series of photographs taken in the field are used to illustrate the characteristics of each unit and associated sub-units in conjunction with details compiled from field and laboratory analyses (Appendix B).

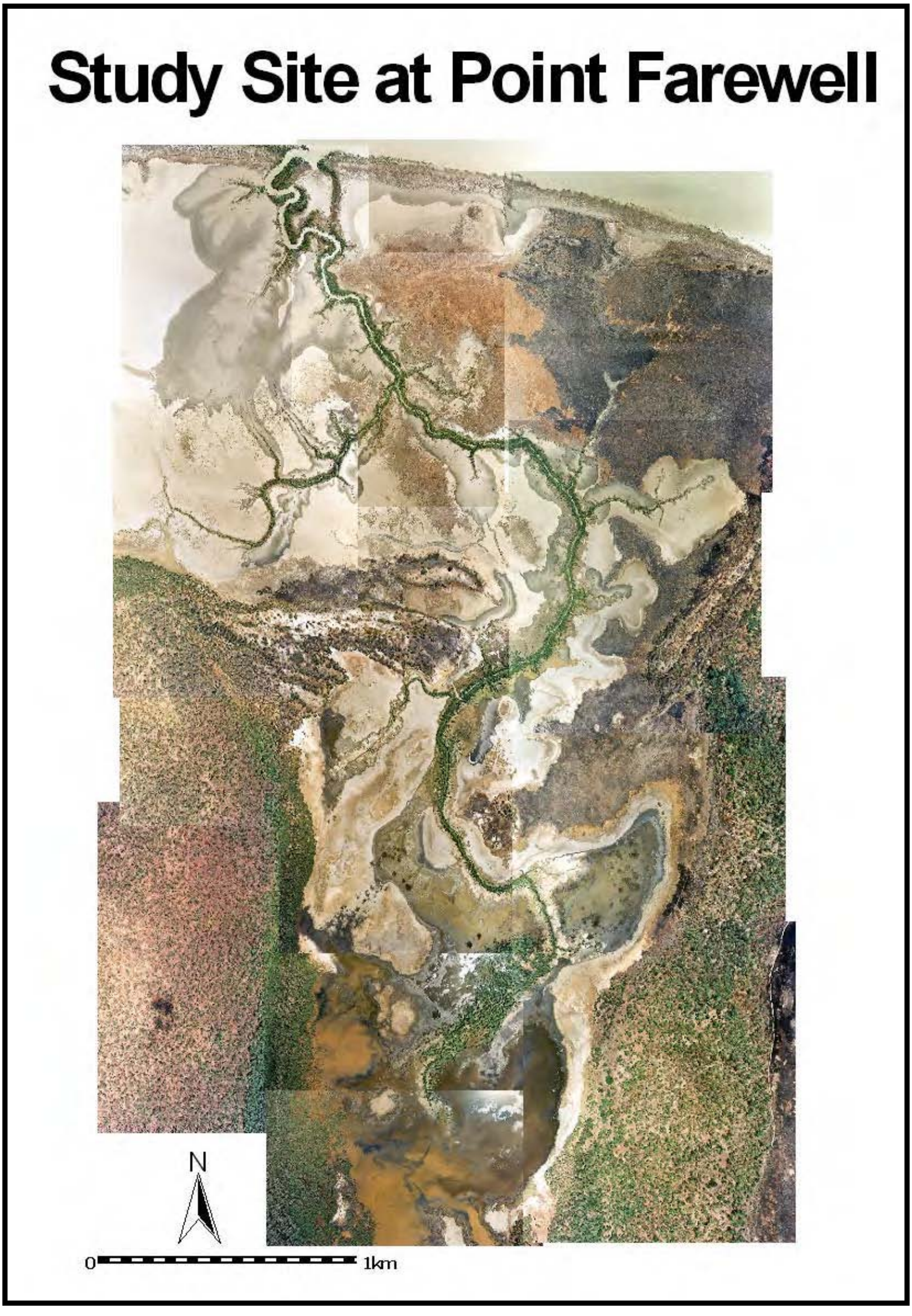

Figure 3.1 **Study Site at Point Farewell**
A mosaic of the 1997 aerial photographs (scale 1:5000) was created in a GIS environment representing the study site at Point Farewell.
(Source: Aerial photographs were obtained from the Environmental Institute of the Supervising Scientist.)

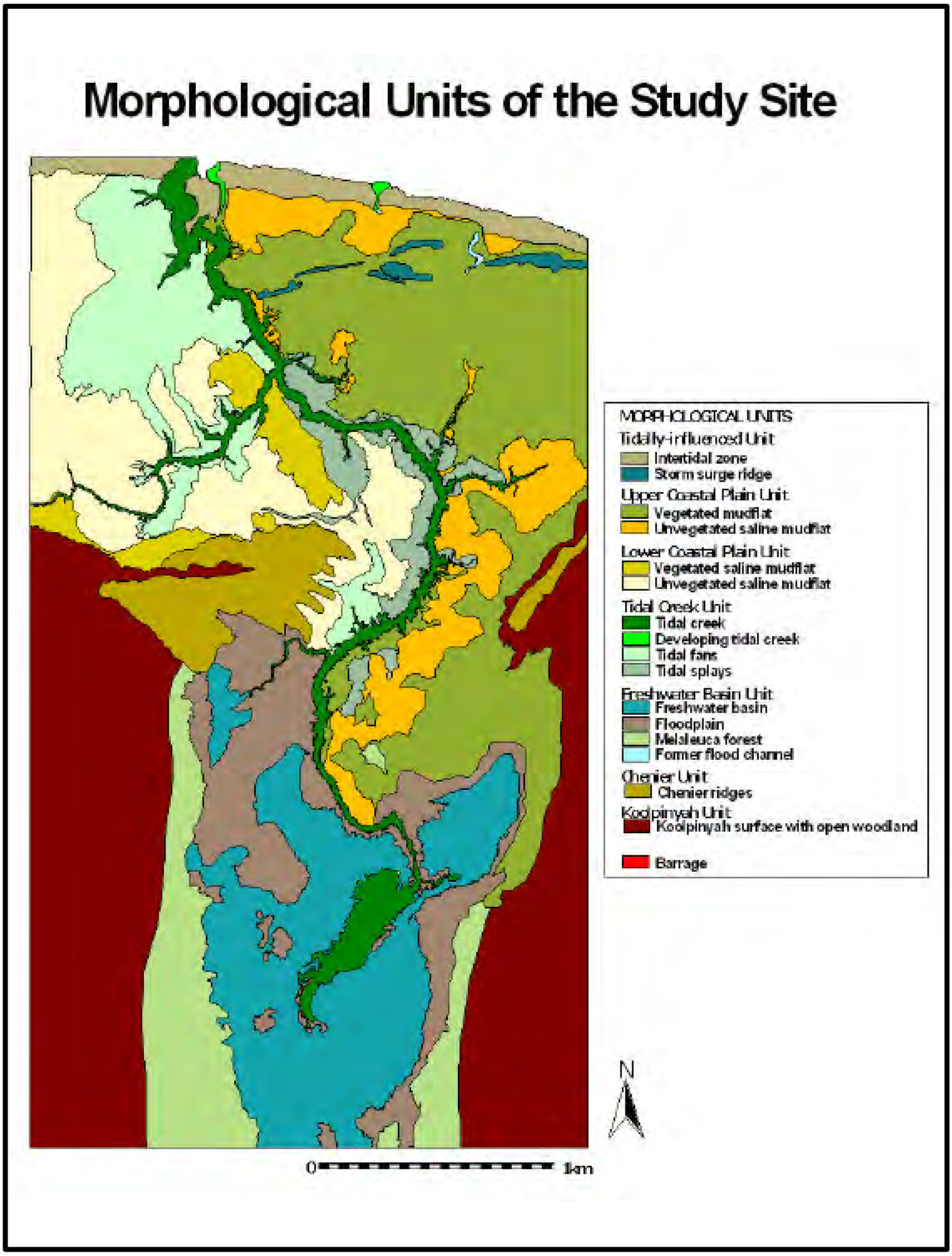

Figure 3.2 Morphological Map of Study Site

Table 3.1 Principal Morphological Units and Associated Sub-Units Contained Within the Study Site

	MORPHOLOGIC DEFINITION	INUNDATION CHARACTERISTICS	OCCURRENCE	SURFACE SEDIMENT CHARACTERISTICS	Vegetation
TIDALLY - INFLUENCED UNIT					
Intertidal Zone	Tidal mudflat and mangroves lining estuarine funnel and fringing the coastal plain.	Tidally flooded; regular inundation	Seaward of the coastal plain and parallel to the estuarine funnel	Not sampled	Mangrove species
Storm Surge Ridge	A band of build-up composed of sand and debris deposited by storm surge events.	Episodic inundation by storm surge events that coincide with spring high tides	Upper Coastal Plain behind intertidal zone	Not sampled	Sedges and grasses
LOWER COASTAL PLAIN UNIT					
Vegetated Saline Mudflat	Sparsely vegetated saline mudflat lying below the level of spring high tides.	Occasional flooding by highest spring tides, storm surges, and tidal flows issued from tidal creek tributaries; inundated by Wet season floods	Localised areas on the Lower Coastal Plain that are not subject to frequent tidal inundation	Dark gray cracking clays; surface sediment is composed of silt (4μm – 63μm) and clay (<4μm) of equal proportions	Sedges and Grasses
Unvegetated Saline Mudflat	Bare saline mudflat lying below the level of spring high tides and subject to frequent inundation with saltwater.	Frequent inundation by tidal flows issued from tidal creek tributaries, spring high tides, and storm surge; inundated by Wet season floods	Dominates the Lower Coastal Plain	Dark gray saline cracking clays; surface sediment is composed of silt (4μm - 63μm) and clay (<4μm) of approximate equal proportions; sediment surface cracks deeply between periods of tidal inundation and dries to desiccation during dry season causing silts and clays to flocculate	Nil
UPPER COASTAL PLAIN UNIT					
Vegetated Mudflat	Densely vegetated mudflat lying at or above the level of spring high tides.	Areas adjacent to unvegetated saline mudflat may be subject to inundation by tidal flows issued from tidal creek tributaries; inundated by Wet season floods	Dominates Upper Coastal Plain	Dark to very dark gray cracking clays; surface sediment is composed of silt (4μm - 63μm) and clay (<4μm), clays dominating the composition; predominantly freshwater clays except for areas adjacent to the unvegetated saline mudflat surface	Sedges and grasses
Unvegetated Saline Mudflat	Isolated pockets of bare saline mudflat lying at or slightly below the level of spring high tides.	Frequent inundation by tidal flows issued from tidal creek tributaries; pockets lying behind intertidal zone are inundated by spring high tides; inundated by Wet season floods	Localised areas lying directly behind intertidal zone and adjacent to tidal creek tributaries on the Upper Coastal Plain	Dark to very dark gray cracking clays; surface sediment is composed of silt (4μm - 63μm) and clay (<4μm) of approximate equal proportions	Nil
TIDAL CREEK UNIT					
Tidal Creek	A narrow mangrove lined tidal channel with a bi-directional flow.	Permanently inundated carrying bi-directional tidal flows	Mouth located along the estuarine funnel and extends landward into the freshwater basin; now physically separated from basin by a barrage	Dark grayish brown clays composed of predominantly silt (4μm - 63μm) and clay (<4μm), which vary in proportion along the length of the tidal creek and tributaries; minor portions of sand may be present along tidal creek banks deposited by tidal flows; upper bank of the tidal creek mouth is composed entirely of sand and shell material	Mangrove species such as *Avicennia marina*, *Lumnitzera racemosa* and *Excoecaria ovalis*
Developing Tidal Creek	A developing tidal channel with a high width to depth ratio that is not stabilised by mangrove.s	Permanently or regularly inundated depending of stage of development, carrying bi-directional tidal flows	Extensive development of tidal creek tributaries on the Lower Coastal Plain	Olive gray clays composed of silt (4μm - 63μm) and clay (<4μm) of varying proportions and varying salt content	Channels are heavily lined by the succulent halophyte, *Batis argillicola*
Tidal Fan	Represents the process of tidal creek tributary development, which is both an erosional and depositional process. Accumulation of sands deposited by tidal flows which issue from confined distributary channels that dissipate their energy and sediment load on the coastal plain in the shape of a fan.	Regularly inundated by tidal flows issued by the distributary channels	Prominent features on the Lower Coastal Plain; no evidence of tidal fans on the Upper Coastal Plain	Distributary channels composed of olive gray saline silt (4μm - 63μm) and clay (<4μm); dark gray saline sandy clays characterize the surface at the heads of the distributary channels which are composed of sand (63μm to 2mm), silt (4μm - 63μm) and clay (<4μm) of varying proportions	Distributary channels are lined predominately with the succulent halophyte, *Bastis argillicola* as well as *Halosarcia indica*, *Halosarcia halocnemoides* and *Sesuvium portulacstrum*
Tidal Splay	Left where surface invasion of saltwater and subsequent scour and deposition of sediment takes place over the coastal plain during high tides.	Localised patterns of inundation associated with tidal flows issued from distributary channels and overbank wash from tidal creek	Present on both the Upper and Lower Coastal Plain	Dark gray saline sandy clays composed of sand (63μm to 2mm), silt (4μm - 63μm) and clay (<4μm) of varying proportions	Bare or sparse clusters of succulent halophytes such as *Bastis argillicola*, *Halosarcia indica*, *Halosarcia halocnemoides* and *Sesuvium portulacstrum*
FRESHWATER BASIN UNIT					
Freshwater Basin	Natural depression holding freshwater from Wet season floods and that issued from freshwater spring.	Permanently inundated with freshwater from Wet season rainfall and that delivered by the freshwater springs	South of chenier unit and confined by the Koolpinyah Unit	Black freshwater clays composed of silt (4μm - 63μm) and clay (<4μm); surface sediments near the waters edge and adjacent to dead trees are composed of sand (63μm to 2mm), silt (4μm - 63μm) and clay (<4μm) of varying proportions	Stands of *Melaleuca* species and dead trees evidence of previous saltwater intrusion
Melaleuca Forest	Stands of *Melaleuca* species inhabiting the freshwater basin.	Periodically inundated during Wet season; forest inhabiting the basin are permanently inundated	Fringing the basin and encroaching towards the basin	Very dark grayish brown to black sandy clays; composed of sand (63μm to 2mm), silt (4μm - 63μm) and clay (<4μm) of varying proportions	*Melaleuca cajuputi*, *Melaleuca viridiflora* and *Melaleuca leucadendra*
Floodplain	A relatively level plain bordering the basin, which is periodically flooded.	Periodically flooded during Wet season	Borders the freshwater basin	Grayish brown saline sandy clays characterize bare sections of the floodplain composed of sand (63μm to 2mm), silt (4μm - 63μm) and clay (<4μm) of varying proportions; vegetated surface is composed of black freshwater sandy clays composed of sand (63μm to 2mm), silt (4μm - 63μm) and clay (<4μm) of varying proportions	Saline sandy clays are bare of vegetation; grasses vegetating freshwater sandy clays
Former Flood Channel	Former channel scoured by flood-waters which is now abandoned and infilled.	Infrequently inundated by spring high tides and Wet season storm surge events	Located on the Upper Coastal Plain	Not sampled	Sedges and grasses
CHENIER UNIT					
Chenier Ridge	Sandy/shelly coastal ridges, deposited by storm.	Rarely flooded	Landward of the coastal plain; present on both sides of the tidal creek	Very dark grayish brown sand	Myrtle-Pandanus Savannah and *Melaleuca* species.
KOOLPINYAH UNIT					
Koolpinyah surface vegetated by open woodland	Low-lying lateritic plain overlying Tertiary sediments and vegetated by open woodland.	Rarely flooded	Confines the freshwater basin	Not sampled	Open woodland; sections of Myrtle-Pandanus Savannah on the eastern side of tidal creek

3.2.1 Tidally-Influenced Unit

The tidally-influenced unit extends along the estuarine funnel and lies seaward of the coastal plain. The unit is composed of two sub-units (1) intertidal zone and (2) storm surge ridge (Figure 3.2). Unfortunately, due to the rise of crocodile encounters during the field investigations this unit was not sampled. Classifications are based on aerial photograph interpretation and visual assessment from the helicopter. Hence, it is possible that with future ground truthing classifications may be subject to alteration.

The intertidal zone includes the tidal mudflat and mangrove belt lining the estuarine funnel and fringing the coastal plain. This sub-unit lies seaward of the coastal plain and is tidally flooded. The dense mangrove belt functions to buffer the coastal plain from erosion and severe flooding as described by Woodroffe and Mulrennan (1993).

The storm surge ridge refers to the band of build-up, composed of sand and debris deposited by storm surge events. This sub-unit is located behind the intertidal zone on the upper coastal plain, and runs sub-parallel to the coast of the Van Diemen Gulf. Storm surge events are non-tidal events, as they result from onshore winds and wind generated set-up, barometric pressure effects and wave set-up. However, when storm surge events coincide with spring high tides, coastal flooding occurs and sediment is deposited by wave action along the upper coastal plain. Hence its inclusion in the tidally-influenced unit. The storm surge ridge is subject to episodic inundation, depending on the occurrence of Wet season storm surge events.

3.2.2 Lower Coastal Plain Unit

The coastal plain is sub-divided into the lower and upper coastal plain based on differences in elevation and processes that are currently active (after Coleman and Wright, 1971). Although elevation is only inferred, the lower coastal plain appears to lie below the level of spring high tides as indicated by the broad expanse of bare surface and extensive development of the tidal creek network. In contrast, the upper coastal plain appears to lie at or above spring high tide level as indicated by the predominantly vegetated surface and limited tidal creek network development.

The lower coastal plain unit is found landward of the intertidal zone on the western side of the tidal creek. This unit is composed of two sub-units (1) vegetated saline mudflat and (2) unvegetated saline mudflat. The reason for using a vegetation criterion is that presence or absence of vegetation reflects the progress of saltwater intrusion on the lower coastal plain. Also, vegetation functions to stabilize the surface, which alters behaviour of sediment during desiccation in the Dry season.

The majority of the lower coastal plain is unvegetated saline mudflat (Plate 3.1) a consequence of extensive tidal creek development. Dark gray saline cracking clays characterise the bare surface, which is composed of both silt (4µm - 63µm) and clay (<4µm). During the Dry season the sediment surface is smoothed by tidal flows (Plate 3.2) and cracks deeply between periods of tidal inundation drying to desiccation (Plate 3.3). In turn, the sediment surface becomes highly susceptible to aeolian processes given the absence of vegetation to stabilise the surface.

Dust storms were prevalent during sediment collection in the field, evidence of aeolian processes (Plate 3.4). As the surface is composed of fine sediment, <63µm, the main mechanism of aeolian transport is 'dispersion' as defined by Pye (1987). When sediment is dispersed into the atmosphere it can travel large distances before it is redeposited. The winds are predominantly from the south to south-east during the Dry season, thus when sediment is entrained it is removed from the system. The removal of sediment by aeolian processes may act to lower the surface of the coastal plain, promoting favourable conditions for tidal creek network development. Although, further research is required to establish the relative contribution of aeolian processes to erosion of the coastal plain. However, these observations will be a good baseline for future research.

A small portion of the lower coastal plain is comprised of the vegetated saline mudflat sub-unit. Vegetation communities consist of sedges and grasses that appear to be retreating as a result of the expansion of the tidal creek network. Succulent halophytes such as *Halosarcia indica, Halosarcia halocnemoides* and *Sesuvium portulacstrum* are encroaching into areas of

LOWER COASTAL PLAIN UNIT

Plate 3.1 **Lower Coastal Plain**
Unvegetated saline mudflat is the dominant sub-unit of the Lower Coastal Plain, a consequence of saltwater intrusion.

Plate 3.2 **Surface Structure of the Saline Mudflat**
The unvegetated saline mudflat is characterized by dried cracking clays, which are smoothed by tidal inundation and dry to desiccation between periods of tidal inundation.

Plate 3.3 **Dry Season Desiccation of Sediment Surface**
During the Dry season the unvegetated saline mudflat cracks deeply and becomes erosionally sensitive.

Plate 3.4 **Dust Storm on the Lower Coastal Plain**
Aeolian transport processes are active on the Lower Coastal Plain where surface sediment is removed from the system by strong south-easterly winds during the Dry season.

Plate 3.5 **Grassland Retreat**
Grasslands of the vegetated saline mudflat sub-unit appear to be retreating and are being replaced by more salt-tolerant species, a consequence of saltwater intrusion.

Plate 3.6 **Dune Formation on the Lower Coastal Plain**
Small dune formations are prominent features of the vegetated saline mudflat sub-unit. Vegetation functions to stabilize the surface and trap sediment deflated from the surface during the Dry season.

retreating grassland (Plate 3.05), towards areas of tidal creek network expansion. As these species prefer sandy substrate with a high salt content (Wightman, 1983) with further tidal creek network development on the lower coastal plain, such species may replace sedge and grass communities.

Vegetation functions to stabilise the sediment surface and acts as a sediment trap. During field investigations, numerous micro-dunes approximately 5cm in height were observed within patches of vegetation (Plate 3.6). Sediment analysis revealed that the colour and size composition mirrored that of the unvegetated saline mudflat. This indicates that although sediment may be deflated from the surface and removed from the system via south-easterly winds it is also retained in the area. However, given that the majority of the lower coastal plain is bare mudflat, a greater amount of sediment may be removed via aeolian processes than is trapped by vegetation during the Dry season. Further work is required to examine this proposition in more detail.

3.2.3 Upper Coastal Plain Unit

The upper coastal plain is located on the eastern side of the tidal creek and landward of the intertidal zone (Figure 3.2). This unit lies at or slightly above spring high tide level and is comprised of two sub-units (1) vegetated mudflat and (2) unvegetated saline mudflat. Unlike the lower coastal plain, the vegetated mudflat is the dominant sub-unit, which may be directly related to the higher elevation of the upper coastal plain and limited tidal creek network development.

Dark to very dark gray cracking clays are present on the vegetated mudflat. The sediments include silt (4µm - 63µm) as well as the clays (<4µm). The surface sediments are predominantly freshwater clays, approximately 17g of NaCl/g of sediment, except for areas adjacent to the unvegetated saline mudflat, which have a high salt content, approximately 100mg of NaCl/g of sediment. The surface is densely vegetated by sedges and grasses, which offer resistance to the sediment surface and limit the degree of cracking. The low salt content of vegetated mudflat supports the inference that the upper coastal plain lies at or above the level of high spring tides.

The unvegetated saline mudflat unit is localised to areas adjacent to tidal creek tributaries (Plate 3.7). Surface sediment characteristics mirror those of the vegetated mudflat except the salt content is much greater, approximately 115g of NaCl/g of sediment. Surface pedding (Plate 3.8) is characteristic of this unit, where silt and clay form strong aggregates that are resistant to dispersion by aeolian processes. Another reason that the sub-unit is less vulnerable to wind erosion than the lower coastal plain may be that frequent inundation by tidal flows may prevent the bare surface from drying to desiccation during the Dry season. There was no evidence of further tidal creek network development within the upper coastal plain unit, in contrast to progressive expansion observed on the lower coastal plain.

3.2.4 Tidal Creek Unit

The tidal creek unit is a prominent feature of the study site. It extends inland from the estuarine funnel into the freshwater basin, providing evidence of saltwater intrusion. However, the unit was separated from the basin by a barrage constructed in 1995. The barrage was constructed to prevent further penetration of tidal waters but is currently being outflanked by the tidal creek. The tidal creek unit is composed of four distinct subunits: (1) tidal splays, (2) tidal fans, (3) developing tidal creek, and (4) main tidal creek. These sub-units represent the progressive development of a tidal creek network, similar to that described by Knighton *et al*. (1992).

Tidal splays are left where surface invasion of saltwater and subsequent scour and deposition of sediment takes place over the coastal plain during high tides. Tidal splays represent the initial stage of tidal scour and channel incision and are prominent features on the lower coastal plain (Plate 3.10). Channel incision is evident on the tidal splay but is relatively indistinct (Plate 3.11). Dark gray saline sandy clays composed of sand (63μm to 2mm), silt (4μm - 63μm) and clay (<4μm) characterise the sediment surface of a tidal splay. Except for the presence of sand, the sediment characteristics are similar to those of the unvegetated saline mudflat of the lower coastal plain, which suggests that tidal flows both deposit and scour sediment as they cover the coastal plain.

UPPER COASTAL PLAIN UNIT

Plate 3.7 **Upper Coastal Plain**
Unvegetated saline mudflat unit is localised to areas adjacent to tidal creek tributaries. In contrast, the vegetated mudflat sub-unit dominates the Upper Coastal Plain, which may be related to the elevation of the plain and thus limited development of the tidal creek network.

Plate 3.8 **Surface Pedding on the Unvegetated Saline Mudflat**
Surface pedding is characteristic of the unvegetated saline mudflat, where silt and clay form strong aggregates. Pedding acts to stabilise the surface, reducing its susceptibility to wind erosion.

TIDAL CREEK UNIT

Plate 3.9 **Tidal Splay**
Saltwater splays across the coastal plain during high tides where the tidal extent is represented by the salt encrusting the surface.

Plate 3.10 **Channel Incision on a Tidal Splay**
Tidal splays represent the initial stage of channel incision by tidal scour. The foam forming around the perimeter of this relatively indistinct tidal channel indicates that incision has been recent, probably only a day old.

Plate 3.11 **Tributary Development**
With continuous tidal action, channels begin to widen and deepen, lengthen and bifurcate.

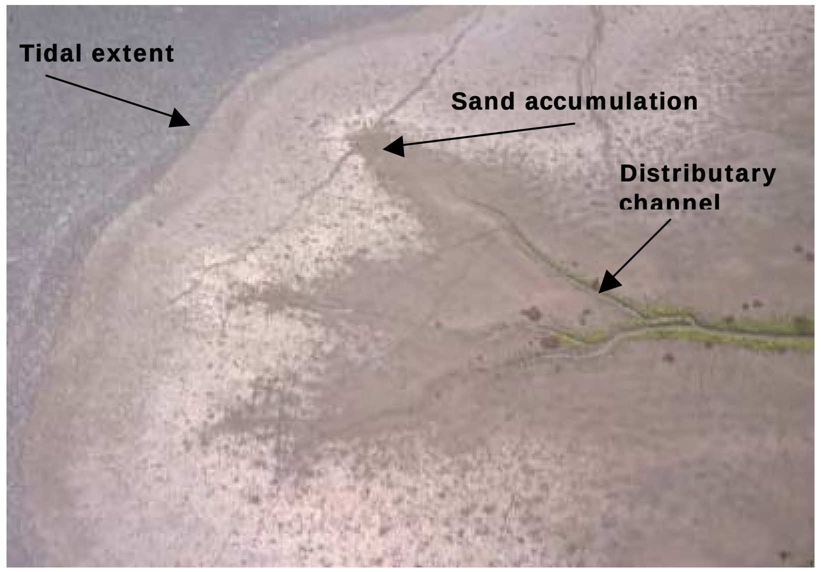

Plate 3.12 **Tidal Fan**
Tidal fans represent the process of tidal creek tributary development, which is both an erosional and depositional process. Sand is deposited by tidal flows which issue from confined distributary channels as tidal creek network evolves.

Plate 3.13 **Colonisation of Tributary by Succulent Halophytes**
Tributary development is associated with encroachment of succulent halophytes, specifically *Batis argillicola*.

Plate 3.14 **Mangrove Encroachment**
Progressive channel development is accompanied by the encroachment of mangroves.

TIDAL CREEK UNIT

Plate 3.15 Developing Tidal Creek Network
Tidal creek network development east of main tida creek system.

Plate 3.16 Mangroves at the Tidal Creek Mouth

Plate 3.17 Mangroves Colonising Tidal Creek West of Barrage

Tidal fans represent the next stage of tidal creek network development, the process of channel formation. Through continuous tidal action, the very shallow channel incisions of tidal splays begin to widen and deepen, lengthen and bifurcate (Plate 3.12). This leads to the formation of distributary channels or alternately the development of tidal creek tributaries. A tidal fan is defined as the accumulation of sands deposited by tidal flows, which issue from confined distributary channels that dissipate their energy and sediment load on the coastal plain in the shape of a fan (Plate 3.13). Sediment analysis revealed the presence of sand at the head of the distributary channels indicating that channel formation and subsequent development are both an erosional and depositional process.

The lower coastal plain has conditions favourable for the continued expansion of tidal creek networks. The plain lies below the level of spring high tides and surface lowering through aeolian transport facilitates further network expansion. Along with the formation of new channels as represented by tidal splays, existing channels are widening and deepening with tidal action. Channel banks are becoming colonised by the succulent halophyte, *Batis argillicola* (Plate 3.14), followed by the encroachment of mangroves (Plate 3.15). Each of the above stages of channel development is represented in Plate 3.16, which is a developing tidal creek east of the main tidal creek network.

Each sub-unit represents a phase of the progressive development of the main tidal creek network. The main tidal creek was defined as a narrow mangrove-lined tidal channel and subsequent tributaries that carries bi-directional tidal flows. Mangroves are characteristic of tidal creek development, where mangrove encroachment along the tidal creek indicates the extent of saltwater intrusion (Cobb, 1997). The height variation in mangroves colonising the main tidal channel and tributaries is also indicative of the advancement of the process of saltwater intrusion. Mangroves colonising the main tidal creek were estimated to be over 3m tall (Plate 3.17) in contrast to those colonising newly formed tributaries, which varied between 80cm and 1.5m depending on the extent of tributary development (Plate 3.18).

3.2.5 Freshwater Basin Unit

The freshwater basin unit is confined by the barrage and chenier unit to the north and by the Koolpinyah unit to the east and west (Plate 3.19). In the past, this unit has been subject to saltwater intrusion through landward extension of the tidal creek. The tidal creek extends into the basin but is currently separated by the barrage. Four distinct sub-units characterise this unit: (1) freshwater basin, (2) floodplain, (3) *Melaleuca* forest and (4) former flood channel. Evidence of saltwater intrusion and the process of recovery are contained within each sub-unit.

The freshwater basin is a permanent water body, holding freshwater from Wet season rainfall and that delivered by the freshwater springs further south of the study area. Water analysis indicates that the water in the basin is predominantly fresh. However, the presence of large stands of dead trees (Plate 3.20), former stands of *Melaleuca* forest, is evidence of the previous saltwater intrusion. Black freshwater clays characterise the surface sediment of the basin, composed of silt (4μm - 63μm) and clay (<4μm). Surface sediment near the water's edge, adjacent to the dead trees is composed of sand, silt and clay. The tidal creek may have deposited the sand as it was extending into the basin. Given that the basin is a natural depression, sand deposited by the tidal creek would have been retained.

A relatively level floodplain borders the basin and is periodically flooded during the Wet season. Two distinct surface sediment units are present, one is an area of previous saltwater intrusion and the other provides an example of the subsequent recovery. Grayish brown saline sandy clays characterise unvegetated sections of the floodplain. This sediment unit forms the outer perimeter of the floodplain and is present throughout the freshwater basin unit. A layer of salt encrusts the surface and dead tree logs are scattered within these areas (Plate 3.21). Black freshwater sandy clays composed of sand, silt and clay characterise the vegetated floodplain. Grasses found in freshwater environments are currently colonising the surface within stands of dead trees (Plate 3.22). This indicates the basin may be recovering from the invasion of saltwater.

FRESHWATER BASIN UNIT

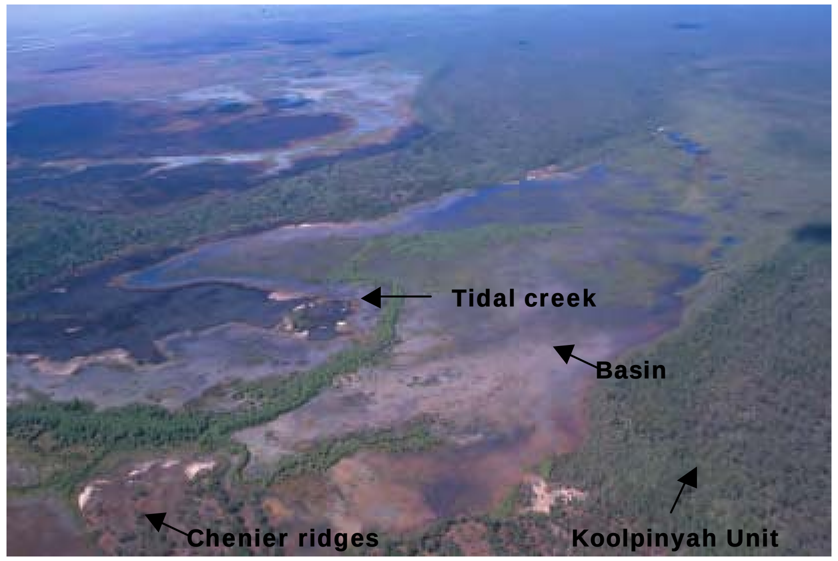

Plate 3.18 **Aerial View of Freshwater Basin Unit**
The freshwater basin is confined by a sequence of chenier ridges to the north and the Koolpinyah unit to the east and west. The landward extent of the tidal creek is visible, evidence of previous saltwater intrusion.

Plate 3.19 **Dead Trees in Freshwater Basin**
The presence of large stands of dead trees, former stands of *Melaleuca* species represent the impact of saltwater intrusion within the basin.

Plate 3.20 **Salt Pan on Floodplain**
A layer of salt encrusts the surface that is composed of sandy clays and scattered by dead tree logs. This is a distinct sediment unit of the floodplain where the presence of sand represents previous deposition by the extending tidal creek.

Plate 3.21 **Revegetation of Floodplain**
Grass species colonizing the floodplain within stands of dead trees, which indicates the basin is slowly recovering from previous saltwater intrusion.

Plate 3.22 ***Melaleuca* Encroachment**
Large stands of *Melaleuca* species are recolonising areas of dieback, immediately south of the chenier ridges.

Plate 3.23 ***Melaleuca* Encroachment**
Large stands of *Melaleuca* species are also encroaching towards the large stands of dead trees within the southern portion of the freshwater basin.

A *Melaleuca* forest borders the floodplain. It contains three species, *Melaleuca cajuputi, Melaleuca viridiflora* and *Melaleuca leucadendra*. Large stands of *Melaleucas* appear to be slowly encroaching into the basin and colonizing areas of dead trees (Plates 3.22 and 3.23). Evidence of *Melaleucas* recolonising areas of dieback suggests that the basin is slowly recovering from saltwater intrusion. Whether the recolonisation is resultant of the barrage and/or variation in Wet season rainfall in the last three years is a question that needs to be addressed.

A former flood channel is visible on the upper coastal plain (Figure 3.2). Interpretation of past aerial photographs indicate that this was a flood channel in 1975, suggesting that the process of saltwater intrusion and subsequent tidal creek extension may have been accentuated by Wet season floods, as suggested by Knighton *et al*. (1993).

3.2.6 Chenier Unit

The chenier unit includes the sequence of chenier ridges present on both sides of the tidal creek, landward of the coastal plain. Cheniers are sandy/shelly coastal ridges, deposited by storm. They mark a period of interruption of the normal muddy progradation of the estuarine shore (Woodroffe and Mulrennan, 1993). Cheniers provide evidence of the former shorelines on the coastal plain. They presumably formed during coastal progradation over the last 4000 years (Woodroffe *et al.*, 1986; Lees, 1987).

Two sets of chenier ridges exist within the study area. On the western side they form a fan-shaped set nearly 1km wide (Plates 3.24 and 3.25) and on the eastern side they closely parallel the Koolpinyah surface (Figure 3.2). Very dark grayish brown sand characterises the surface sediment of the chenier ridges. The dark colour of the sand is due to the presence of charcoal as the study site was being deliberately burnt during sediment collection. The chenier ridges dam the freshwater and hold large volumes of Wet season runoff and rainfall, retaining it long into the Dry season. Thus the presence of the chenier ridges may be contributing to the recovery process occurring within the freshwater basin.

CHENIER UNIT

Plate 3.24 **Chenier Ridges on Western Side of Study Site**
Chenier ridges form a fan-shaped set and confine the freshwater basin, forming a natural barrier between the coastal plain and freshwater basin.

Plate 3.25 **Rise of Chenier Ridges**
The slope of vegetation illustrates the rise of chenier ridges which are approximately 2 metres above the Lower Coastal Plain.

3.2.7 Koolpinyah Unit

The Koolpinyah unit is a term used to refer to the lateritic plains formed over Late Tertiary sediments, vegetated with open woodland (Story *et al.*, 1969). The Koolpinyah unit confines the freshwater basin and is rarely flooded. This unit was not sampled due to time constrictions in the field. However according to a vegetation survey undertaken by Schodde *et al.* (1987), the surface is vegetated with open woodland with sections of Myrtle-Pandanus Savanah on the eastern side.

3.3 Morphological Changes Between 1997 and 2001

The morphological units were mapped from the 1997 aerial photographs and ground-truthed in 2001. Unit boundaries were reassessed in the field and appear to have remained unchanged. However, several changes were observed to be occurring within the lower coastal plain, freshwater basin and tidal creek units. These changes proved difficult to map due to their small-scale. Hence a series of photographs taken in the field are used to illustrate the observed changes (Figure 3.3).

The expansion of the tidal creek network is currently active on the lower coastal plain. Various stages of channel development were observed. These ranged from indistinct channel incisions of tidal splays to developing tidal creek tributaries associated with tidal fans. However, no evidence of recent tidal creek network development was observed to be occurring on the upper coastal plain. The further network development on the lower coastal plain may be the result of increasing water levels in the Van Diemen Gulf over the last three years.

Normalised monthly water levels recorded in the Darwin Harbor between 1993-2000 are illustrated in Figure 3.4 and are used as a surrogate for the water levels in the Van Diemen Gulf. There appears to be a progressive rise in monthly water levels since 1998 which may be contributing to tidal creek development on the Lower Coastal Plain. Also, above average Wet Season rainfall has been experienced for the last two Wet seasons, as illustrated in Figure 3.5. Wet season rainfall on the coastal plain and subsequent drainage through the developing tidal channels accentuate channel incision.

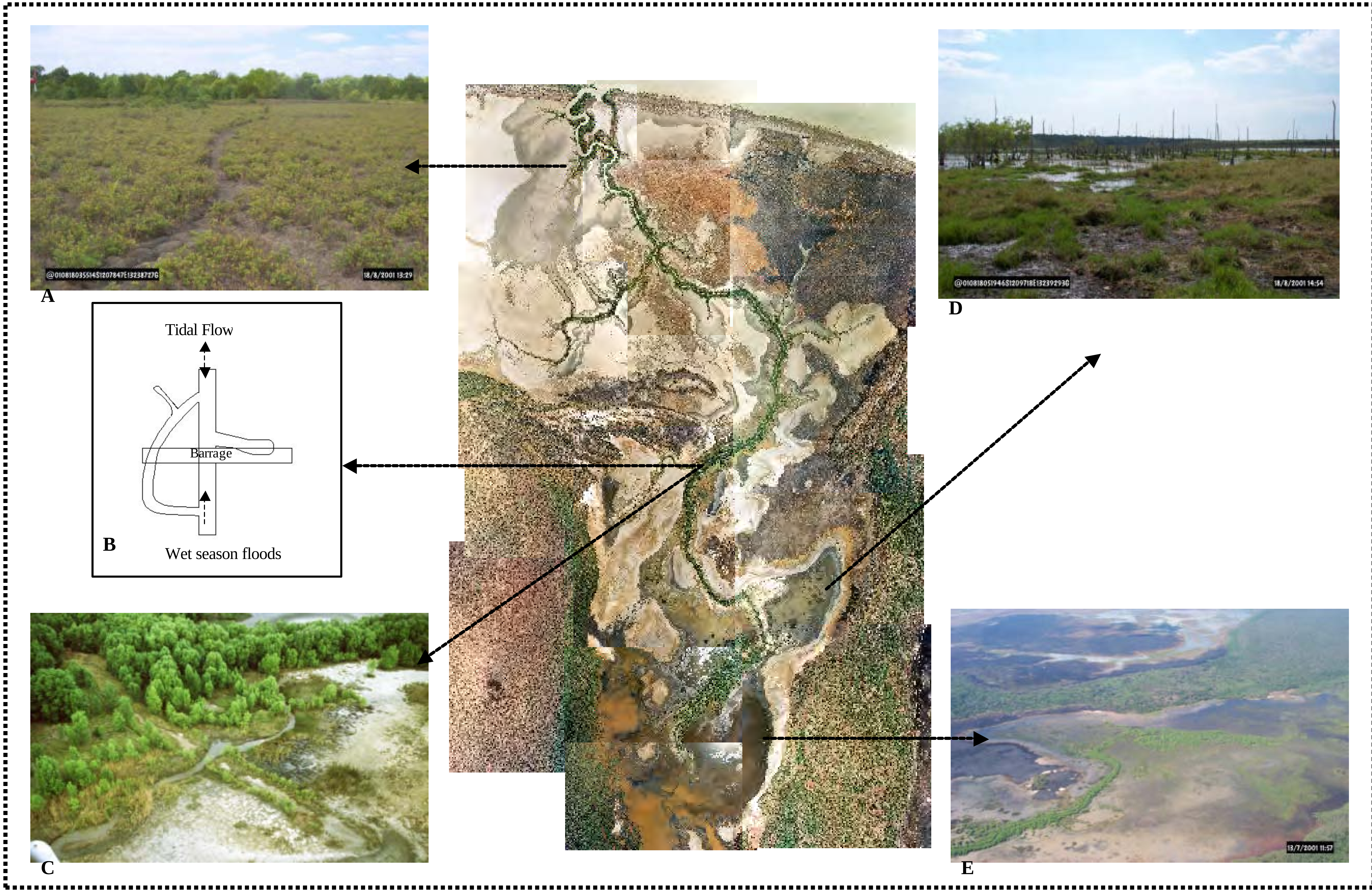

Figure 3.3 Morphological Changes at the Study Site Between 1997 and 2001
The morphological changes that have occurred since 1997 include: (A) tidal creek tributary development on the Lower Coastal Plain, (B) and (C) tidal creek is now outflanking the barrage allowing the penetration of saltwater into the freshwater basin and drainage of freshwater from the basin (D) the freshwater basin is showing signs of recovery such as floodplain revegetation with grasses and recolonisation of *Melaleucas* and (E) the basin is holding more freshwater.

The tidal creek is currently outflanking the barrage. This suggests that saltwater may be currently intruding into the freshwater basin during periods of high water level. It was the motivation behind using ^{228}Th-^{226}Th isotope technique. Unfortunately the results are not available for this thesis as the concentrations have not yet been determined by gamma spectrometry. While time restrictions prohibit the inclusion of the results in this thesis they will be available for future drafts of this body of work.

At the time of the ground survey the freshwater basin appeared to hold more water than was evident in the aerial photographs. This could be associated with a number of factors. First, the aerial photographs were flown at the end of the Dry season, October 1997 and ground-truthing was undertaken during the middle of the Dry season, July-August 2001. Second, Wet season rainfall between 1999-2001 has been well above-average, with approximately 500mm increase within this time period (Figure 3.5). Thus the basin would be holding more water and the presence of the cheniers would have functioned to dam surface run-off and retain it well into the Dry season.

Finally, the barrage may be a contributing factor. Barrages have been used as short-term solutions for managing saltwater intrusion. The history of the barrage at the study site illustrates that its effectiveness in managing saltwater is strongly influenced by climatic and oceanographic variables. In theory, the barrage forms a physical barrier separating the tidal creek from the freshwater basin. It prevents further penetration of saltwater and aids in freshwater retention. The barrage was constructed in 1995 and was cut through in the same year. Its failure may be related to the above average Wet season rainfall and water levels in the Gulf experienced in 1995 (Figures 3.4 and 3.5). The barrage was rebuilt and appears to be stable, except that the tidal creek is now outflanking it.

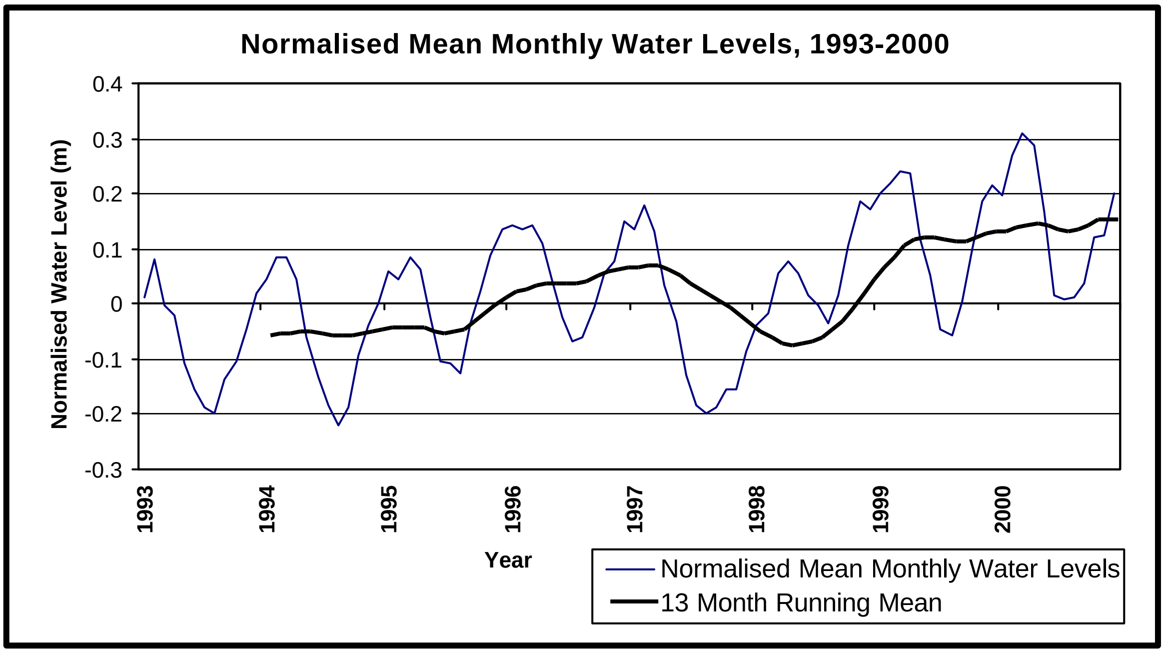

Figure 3.4 **Normalised Mean Monthly Water Levels from Darwin Harbour, 1993-2000**
The 13 month running mean indicates in the Darwin Harbour water levels were increasing between 1998-2000.
(Source: National Tidal Facility, 2001)

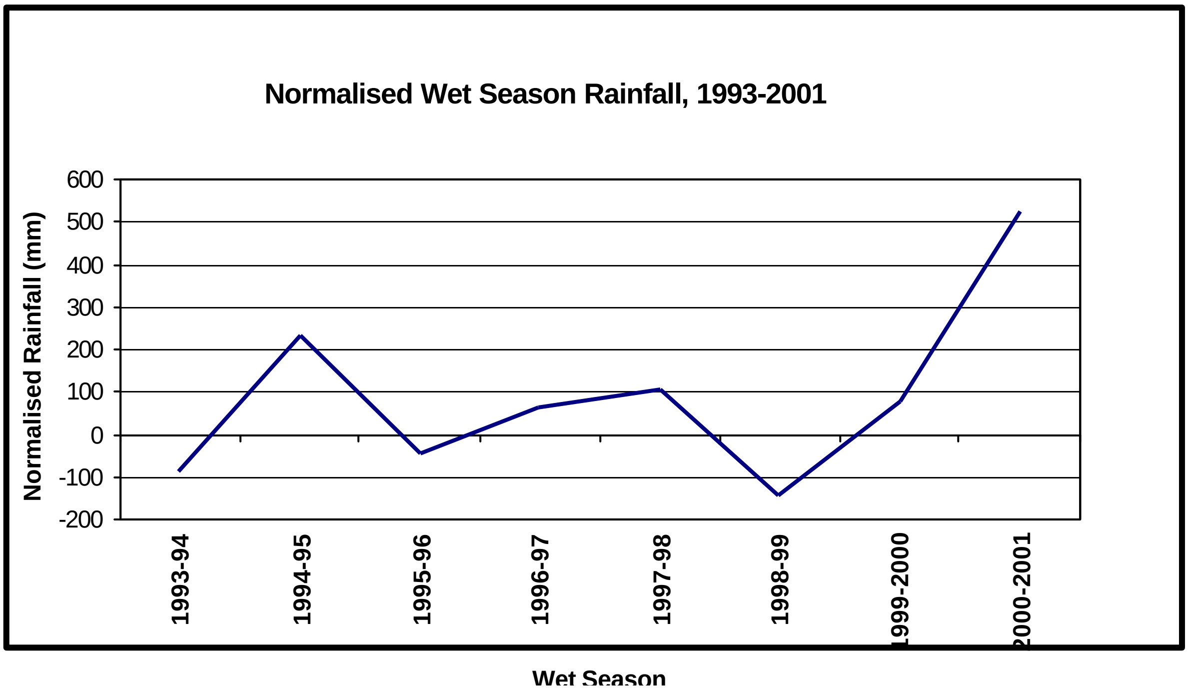

Figure 3.5 **Normalised Wet Season Rainfall for Oenpelli, 1993-2001**
Between 1999-2001 Wet season rainfall (November to March) as recorded for Oenpelli, has experienced well above average rainfall.
(Source: Bureau of Meteorology, 2001)

CHAPTER 4: HISTORICAL MORPHOLOGICAL CHANGE AT POINT FAREWELL

4.1 Organisation of Results

Morphological changes that have occurred since saltwater invaded the freshwater basin at Point Farewell were reconstructed within a GIS environment from aerial photographs for the years 1950, 1975, 1984 and 1997. The changes are presented in a series of morphological maps, scale 1:15,000, and estimates of change between each time period are given as percentages. They were analysed in conjunction with climatic and oceanographic datasets to assist in identifying the potential processes driving them.

4.2 Morphological Change, 1950-1997

The study site at Point Farewell has undergone significant morphological change in the past. Saltwater intrusion has been an active process over the last 50 years and has contributed to the changes identified from the aerial photographs. The morphology of the study site in 1950 is described below and the subsequent changes between each time period are assessed.

4.2.1 Morphology of Study Site in 1950

In 1950, the study area (Figure 4.1a) was composed of 6 distinct morphological units and associated subunits (Figure 4.1b). The tidally-influenced unit included the intertidal zone, a series of natural levee banks and a storm surge ridge (or incipient chenier ridge). A series of natural levee banks paralleled the estuarine funnel and lay directly landward of the intertidal zone. Levee banks are natural riverbanks deposited by overbank wash during Wet season floods. Levee banks would have hindered tidal and fluvial flooding of the coastal plain under less than bankfull floods. The storm surge ridge was located landward of the natural levee banks on the western side of the tidal creek. This ridge is chenier-like in appearance and has been subject to surface modification. It would have been composed of sand and debris deposited by storm surge events. Its presence indicated that storm surge events were prominent at the study site.

No distinction between the Upper and Lower Coastal Plain was evident in the 1950 aerial photographs. Instead the coastal plain was one unit that was dominated by vegetation, probably sedges and grasses. Pockets of unvegetated saline mudflat were localised to areas adjacent to the developing tidal creek network.

The tidal creek had a well-developed mouth and was lined by dense stands of mangroves. The landward extent of the tidal creek extended 1 km inland from its opening at the estuarine funnel of the East Alligator River. Development of the tidal creek network was occurring on the western side of the main tidal creek. Evidence of network expansion consisted of distinct tidal tributary channels and bare saline mudflats in the near vicinity. There was no distinct connection between the freshwater basin and the tidal creek.

The freshwater basin consisted of a string of billabongs confined by the Koolpinyah unit, flowing onto the coastal plain to within 300 m of the extending tidal creek. The seaward extent of the freshwater basin appeared to be buffered from the headward saline expansion by alluvium and vegetation (Figure 4.1a), as proposed by Heerdegen and Hill (2000). When viewed stereoscopically the area is elevated and could represent a build-up of alluvium deposited from the freshwater stream during Wet season floods. Large stands of *Melaleuca* forests inhabited the freshwater basin and small pockets of vegetated floodplain bordered the basin.

Palaeochannels were present on the coastal plain, located north of the chenier spits. These were previously active tidal channels on the palaeocoastal plain. The palaeochannels were disconnected from the developing tidal creek network and appear to be partially infilled. These low-lying areas either remained wet throughout the year or dried out and became saline mudflats. Both were thus susceptible to saltwater intrusion as suggested by Woodroffe and Mulrennan (1993).

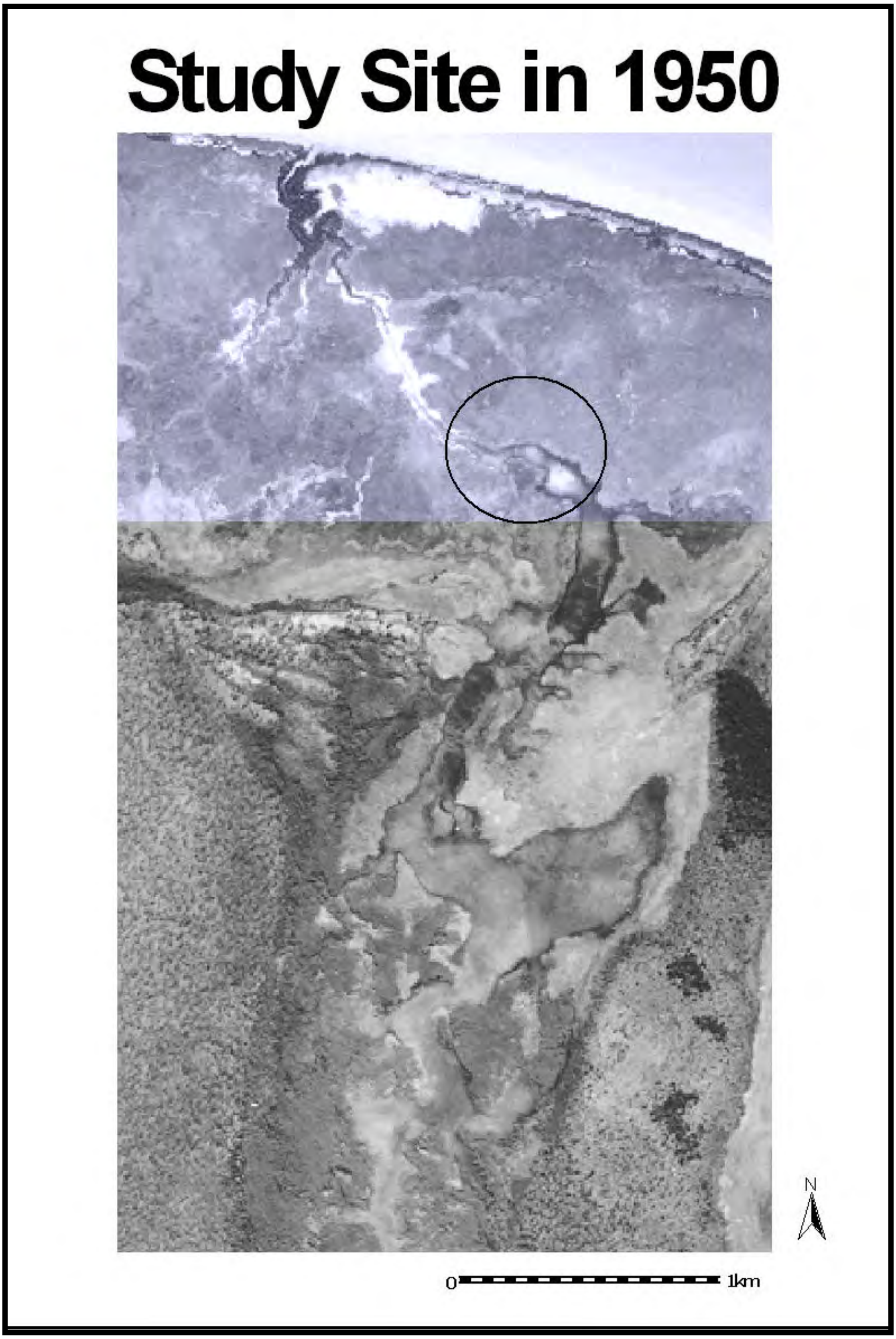

Figure 4.1a **Study Site at Point Farewell in 1950**
The circle represents the possible buffer zone of alluvium and vegetation.
(Source: Aerial photographs were obtained from the Environmental Institute of the Supervising Scientist).

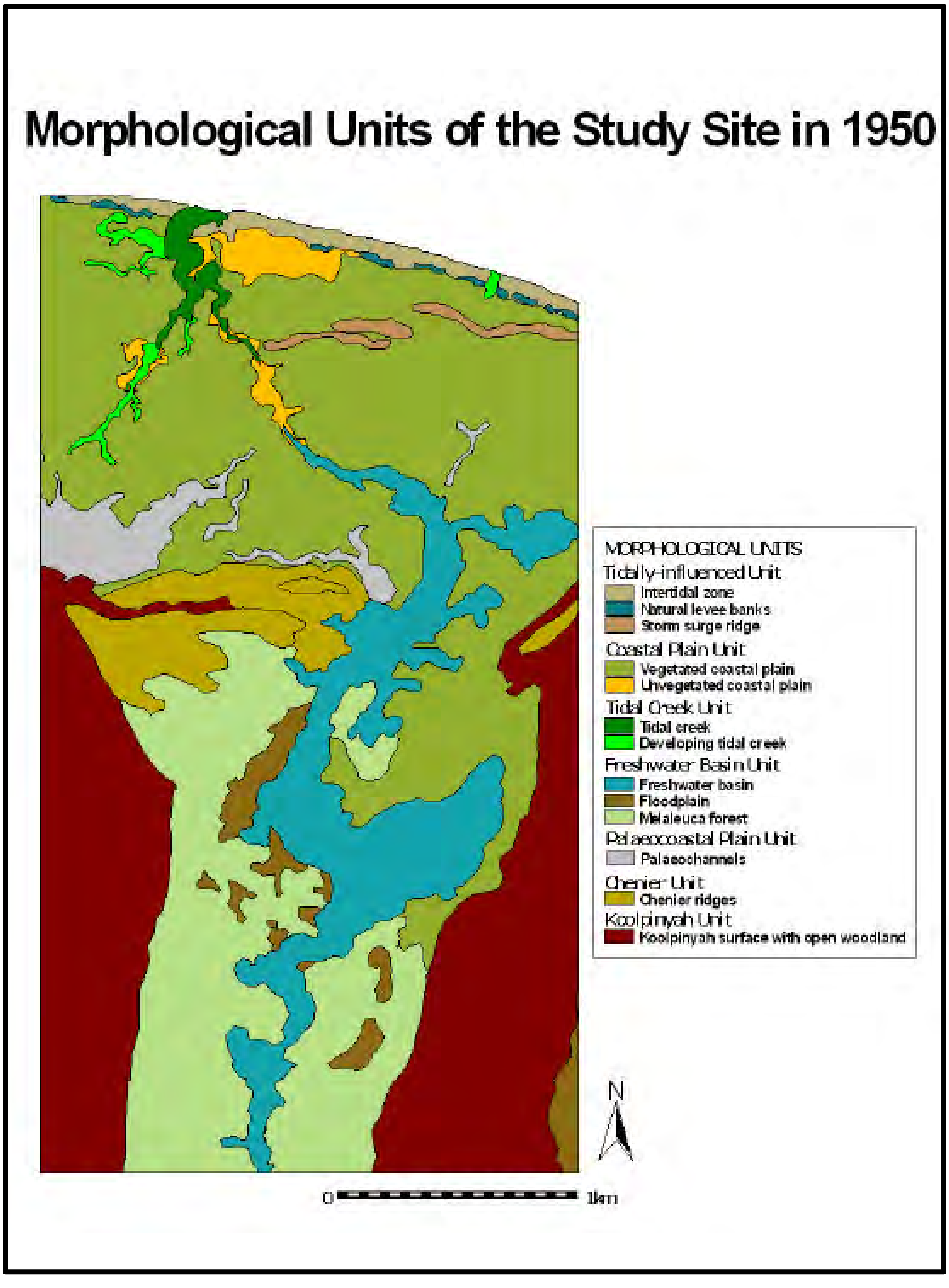

Figure 4.1b Morphological Map of the Study Site in 1950

The fan-shaped sequence of chenier ridges on the western side formed a natural barrier protecting areas of the freshwater basin from tidal processes and aided in freshwater retention. Dense stands of *Melaleuca* forest inhabited the areas between and immediately south of the ridges.

4.2.2 Morphological Change, 1950-1975

Between 1950 and 1975 saltwater invaded the freshwater basin (Figures 4.2a and b). The main tidal creek, as indicated by the mangroves flanking the channel had extended 75 m. However, an incised channel was cut a further 1 km inland and the freshwater basin made saline. This is indicated by the loss of *Melaleuca* forest immediately south of the chenier ridges (Figure 4.2b). Approximately 45% of the Melaleuca forest present in 1950 was lost.

Expansion of the tidal creek network is apparent from the aerial photography. It appears more extensive on the western side of the tidal creek, indicating that this part of the coastal plain was at a lower elevation than the eastern side. Thus a distinction between the Lower and Upper Coastal Plain was made when creating the morphological map (Figure 4.2b). The surface invasion of saltwater associated with the expansion of the tidal creek network resulted in the loss of approximately 41% of the vegetation present in 1950. The loss of vegetation resulted in the exposure of the underlying saline mudflat. By 1975 the area occupied by saline mudflat had increased by 906%.

The presence of flood channels in 1975 suggests that Wet season floods prior to the date of the aerial photography had facilitated the headward extension of the developing tidal creek. The flood channels had cut through the area of alluvium deposition (Figure 4.2a) that previously buffered the freshwater basin from the headward extension of the tidal creek. The flood channels provided potential routes for channel incision of the tidal creek. Also between 1950 and 1975, the flood channels had cut into the palaeochannels on the Lower Coastal Plain (Figures 4.1b and 4.2b). These are apparent in Figure 4.1b. They provided a principal route for the flood channel that breached the storm surge ridge in 1975 (Figure 4.2b).

Figure 4.2a **Study Site at Point Farewell in 1975**
The circle represents the breaching of the buffer zone by flood channels.
(Source: Aerial photographs were obtained from Parks Australia North.)

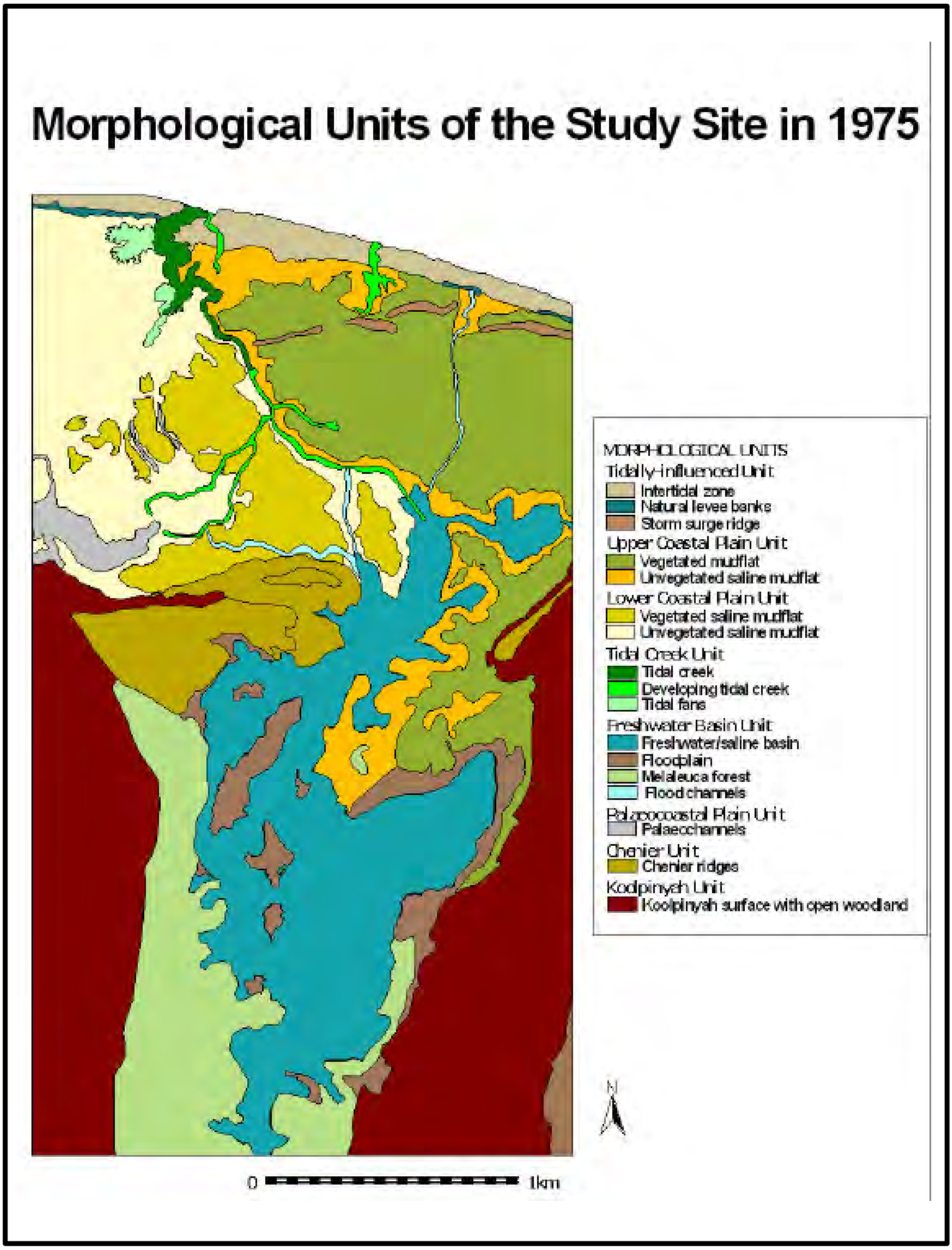

Figure 4.2b Morphological Map of Study Site in 1975

Approximately 33% of the natural levee banks present in 1950 had been washed away by 1975.

4.2.3 Morphological Change, 1975-1984

Rapid landward extension of the tidal creek network occurred between 1975 and 1984. In less than 10 years an incised tidal creek channel extended a further 2km inland (Figures 4.3a and 4.3b). One proposition is that the rapidity of the headward extension could be attributed to the break down of the buffer zone by the flood channels in 1975 and the presence of palaeochannels. The palaeochannels seem to provide principal routes for network expansion (Figures 4.2b and 4.3b) and controlled the lines along which tidal processes most likely operated between 1975 and 1984.

Tidal creek network expansion on the Lower Coastal Plain was accompanied by a further reduction in vegetation and an increase in unvegetated saline mudflat. Network expansion also occurred on the Upper Coastal Plain but to a lesser degree. By 1984 approximately 65% of vegetation present in 1975 had been lost from the coastal plain. The area occupied by unvegetated saline mudflats in 1975 had increased by 44%.

A further 26% reduction in *Melaleuca* forest occurred after 1975 and the basin was holding approximately 70% less water. The lack of freshwater retention and increase saline influence may have contributed to the reduction of *Melaleuca* forest. As tidal channels carry bi-directional flows, the tidal creek network would have drained freshwater from the basin on every ebb tide. However, Wet season floods act to force saltwater out of the system, hence the loss of *Melaleuca* forest may have resulted from the lack of freshwater rather than saltwater intrusion given that that *Melaleuca* species, specifically *Melaleuca cajuputi* and *Melaleuca viridiflora* are salt-adapted species (Lynch, 1997). Stands of *Melaleuca* forests were localised to areas of the basin that were still inundated, presumably by fresh or brackish water (Figure 4.3b).

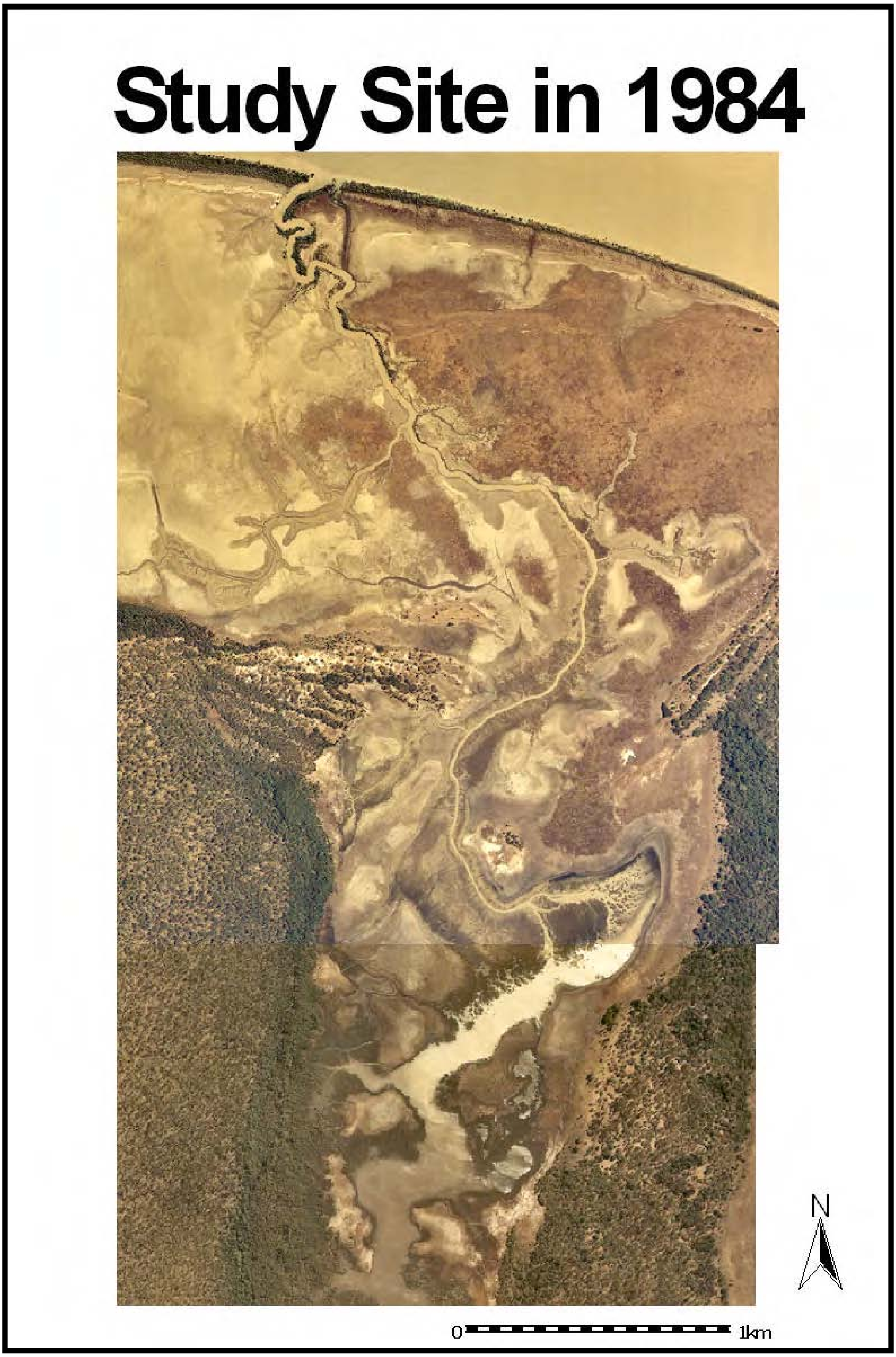

Figure 4.3a **Study Site at Point Farewell in 1984**
(Source: Aerial photographs were obtained from Parks Australia North.)

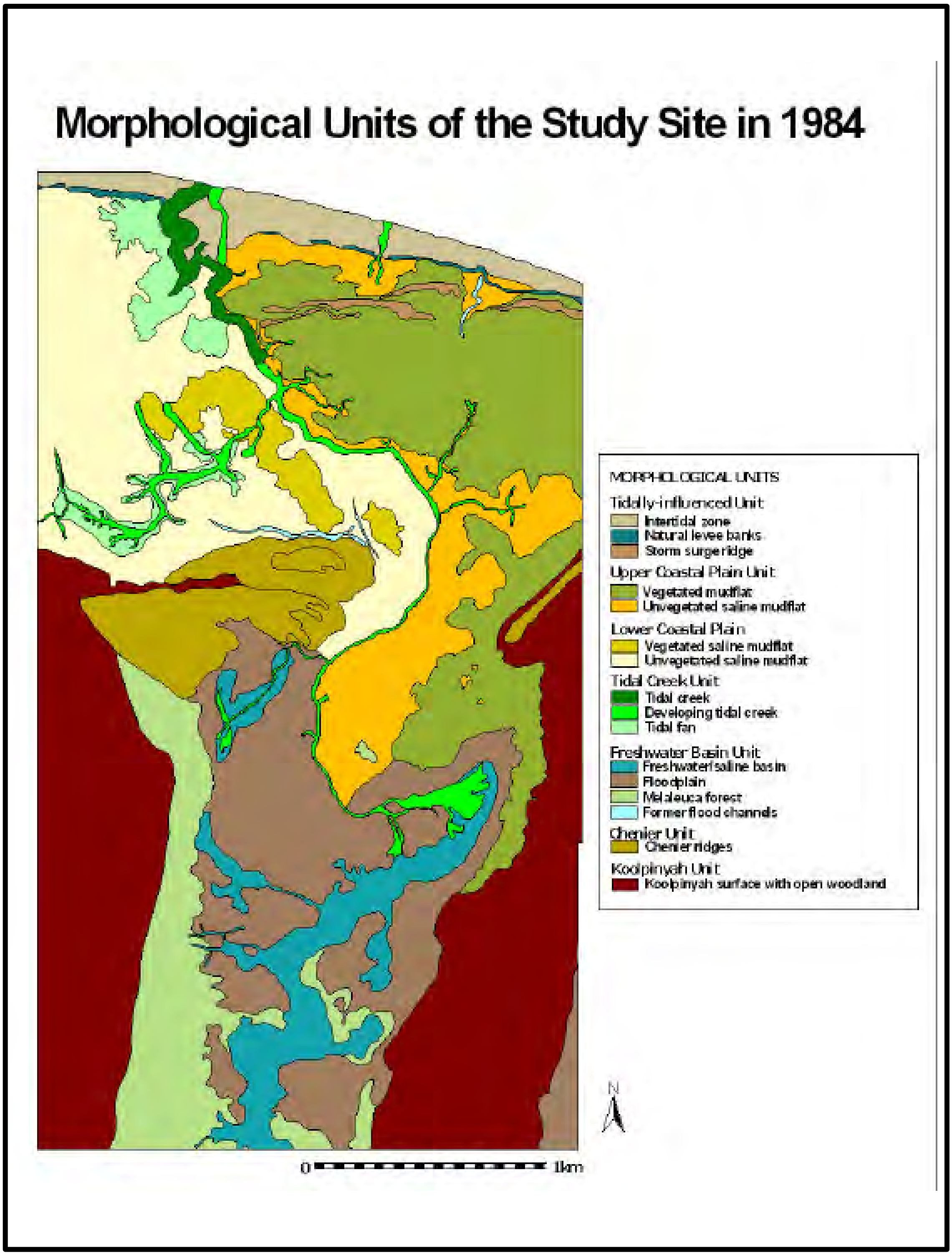

Figure4.3b Morphological Map of the Study Site in 1984

4.2.4 Morphological Change, 1984-1997

By 1997 the tidal creek had incised its channel 1 km beyond that shown in 1984 (Figures 4.4a and 4.4b). This is an apparent slowing of the rate of extension. The tidal creek was mangrove lined, indicating the extent of saltwater intrusion and the barrage prevented further landward extension.

Tidal fans present on the Lower Coastal Plain provide evidence of progressive network expansion, but not to the degree experienced prior to 1997. There was no further network development on the Upper Coastal Plain, which may account for the 15% increase in vegetation observed. The higher elevation of the Upper Coastal Plain would have limited network expansion.

Morphological changes that occurred between 1985 and 1997 were not as extensive as with previous time periods. This may indicate that the system was achieving a new balance between freshwater and tidal regimes during this period. However, barrage construction in 1995 may have interfered with and offset further morphological change to some extent.

4.3 Climatic and Oceanographic Conditions, 1966-1997

Wet season rainfall for Oenpelli and mean monthly water levels for Darwin are used as surrogate datasets for the conditions experienced at Point Farewell between 1966 and 1997. Prior to 1966, the mean monthly water level data for Darwin were incomplete. To ensure comparability of the information, 1966 to 1997 was used as the common period of time for the analysis. Cyclonic data for the Northern Territory is also used to gain insight into the conditions experienced during the time span of the aerial photography.

4.3.1 Wet Season Rainfall, 1966-1997

Wet season rainfall events for the months November to March, between 1966-1997 were normalised to determine the frequency of above and below average Wet season rainfall events (Figure 4.5). Between 1966 and 1997, 40% of the Wet season rainfall events were above-average. Wet season

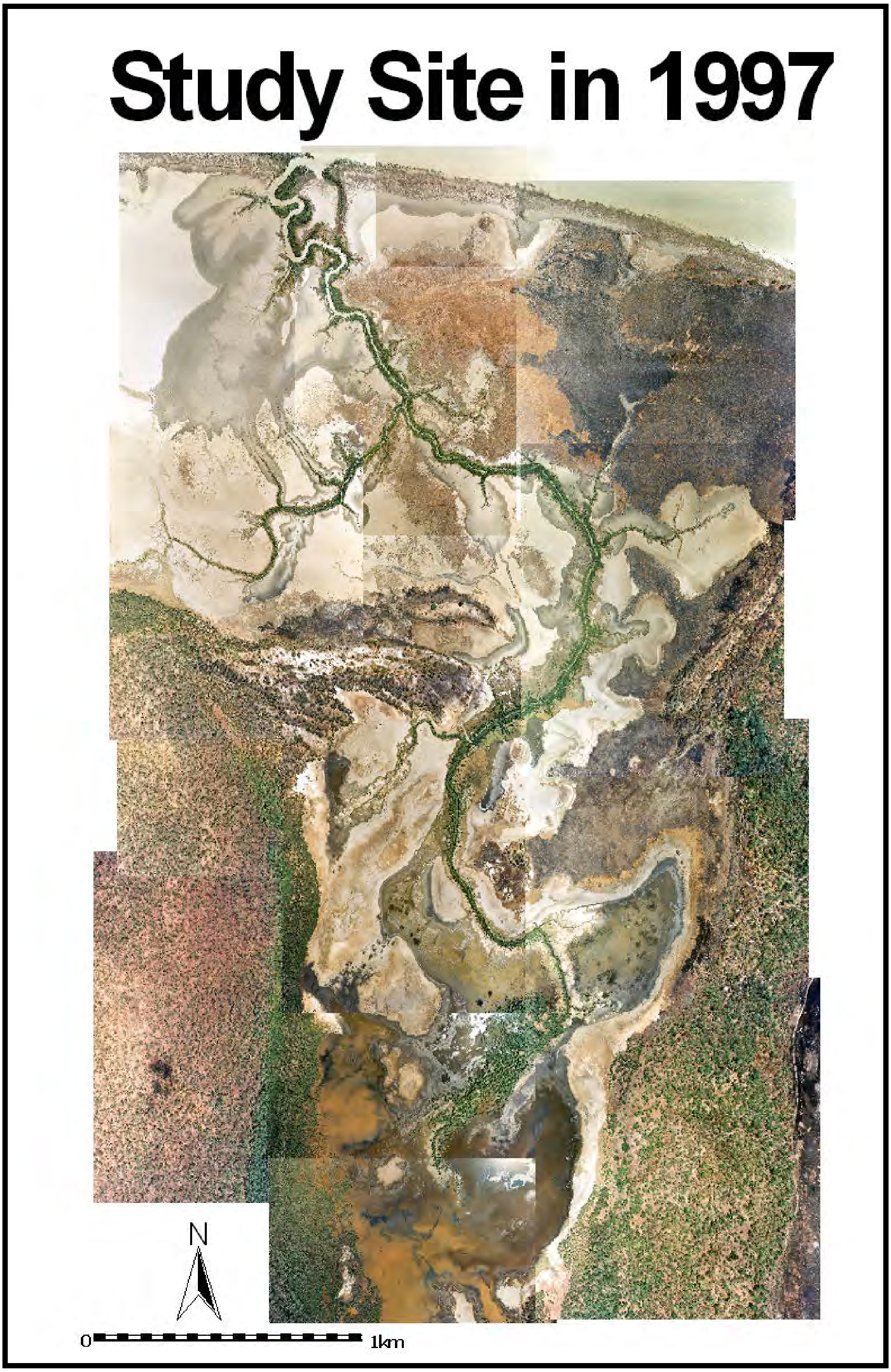

Figure 4.4a **Study Site at Point Farewell in 1997**
(Source: Aerial photographs were obtained from the environmental Institute of the Supervising Scientist.)

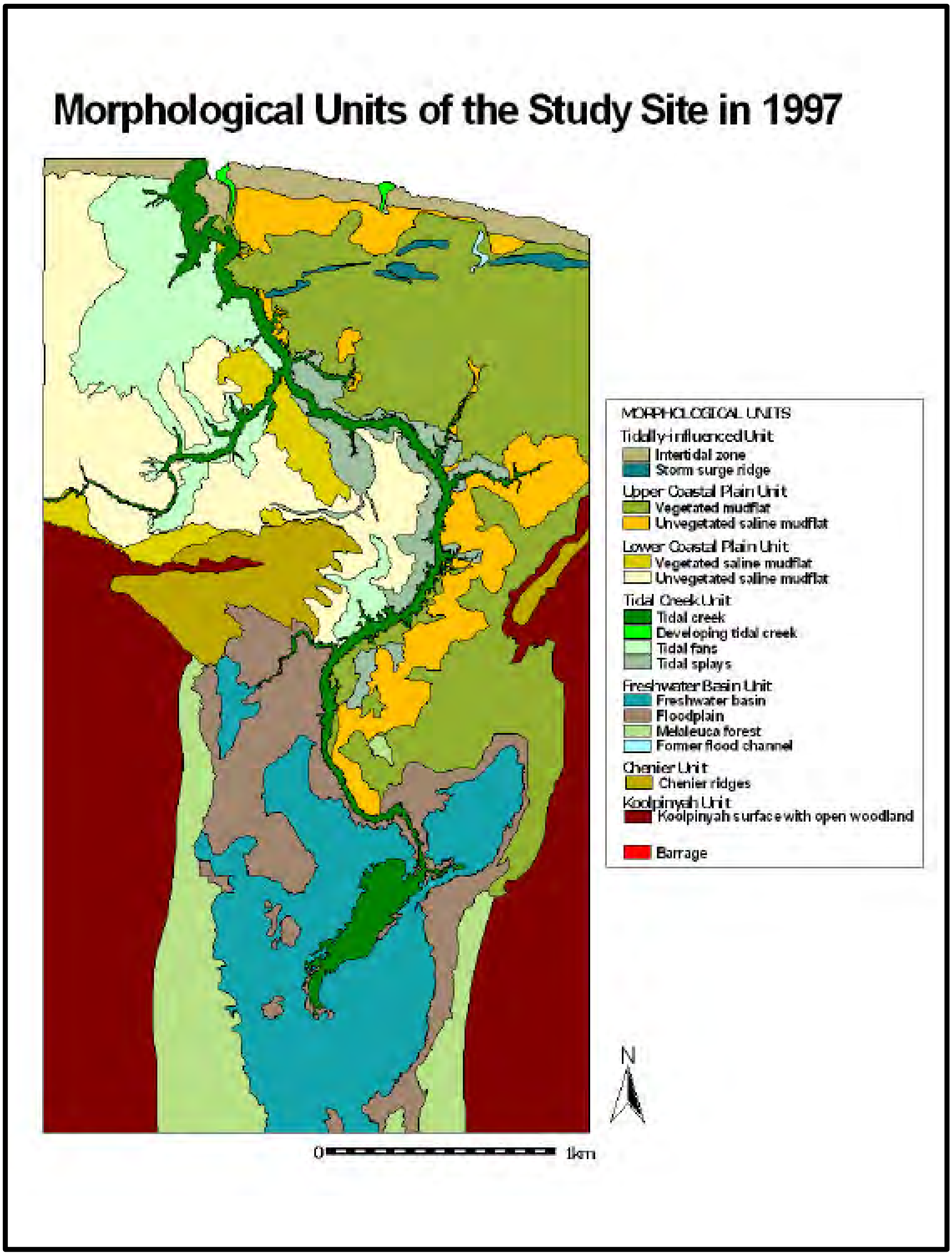

Figure 4.4b **Morphological Map of the Study Site in 1997**

rainfall was well above-average between 1973 and 1975, prior to when the aerial photography was taken. Smoothing of the data with a five period running mean indicates that Wet season rainfall was progressively increasing. Between 1975 and 1984, 67% of the Wet season rainfall events were above-average (Figure 4.5). However the five period running mean indicates Wet season rainfall was progressively declining following the 1976-1977 Wet season. The majority of the Wet season rainfall events between 1984 and 1997 were below-average and 30% above-average. The declining trend in Wet season rainfall continued until 1989-1990 where it then began to rise.

4.3.2 Mean Monthly Water Levels, 1966-1997

Mean monthly water levels for Darwin were normalised to determine the frequency of above and below average water levels experienced between 1966 and 1997 (Figure 4.6). Between 1966 and 1975, just under 50% of above-average monthly water levels experienced were 15cm to 20cm higher than average. About 40% of the above-average water levels occurred three years prior to aerial photographs (1973-1975). Also, there appears to have been a progressive yearly increase in water levels since mid-1973. Between 1975 and 1984, 50% above average monthly water levels were experienced. However, the above average water levels experienced during this time period were only half the amplitude of those that occurred during 1966 and 1975. The thirteen-month running mean indicates that there was a progressive decline in water levels during this period. Between 1984 and 1997, water levels fluctuated between above and below average and just under 50% above-average mean monthly water levels were experienced, most of which were 10cm higher than average. The majority of the above-average water levels were less than 10cm.

4.3.3 Cyclonic Events, 1966-1997

Cyclone data for the Northern Territory were used to determine the frequency and duration of cyclone events that occurred during the Wet season between 1966 and 1997. Also, the frequency of extreme cyclones, those with a barometric pressure less than 1000 hPa, was determined from the data.

A high frequency of low intensity cyclones was experienced between 1966 and 1975 (Figure 4.8). Around 2 cyclonic events were experienced per Wet season with an average duration of 5 days (Figure 4.7). Three extreme cyclonic events occurred during the 1974-1975 Wet season, the most extreme being cyclone Tracey, several months prior to the aerial photography.

Between 1975 and 1984, 10 cyclonic events occurred during 9 Wet seasons, 50% of which were of low extremity (Figure 4.7 and 4.8). A frequency of one cyclonic event per Wet season occurred between 1984 and 1997 (Figure 4.7). The majority of these were of low extremity (Figure 4.7). However, the cyclone experienced during the 1991-1992 Wet season was of similar intensity to cyclone Tracey (figure 4.8).

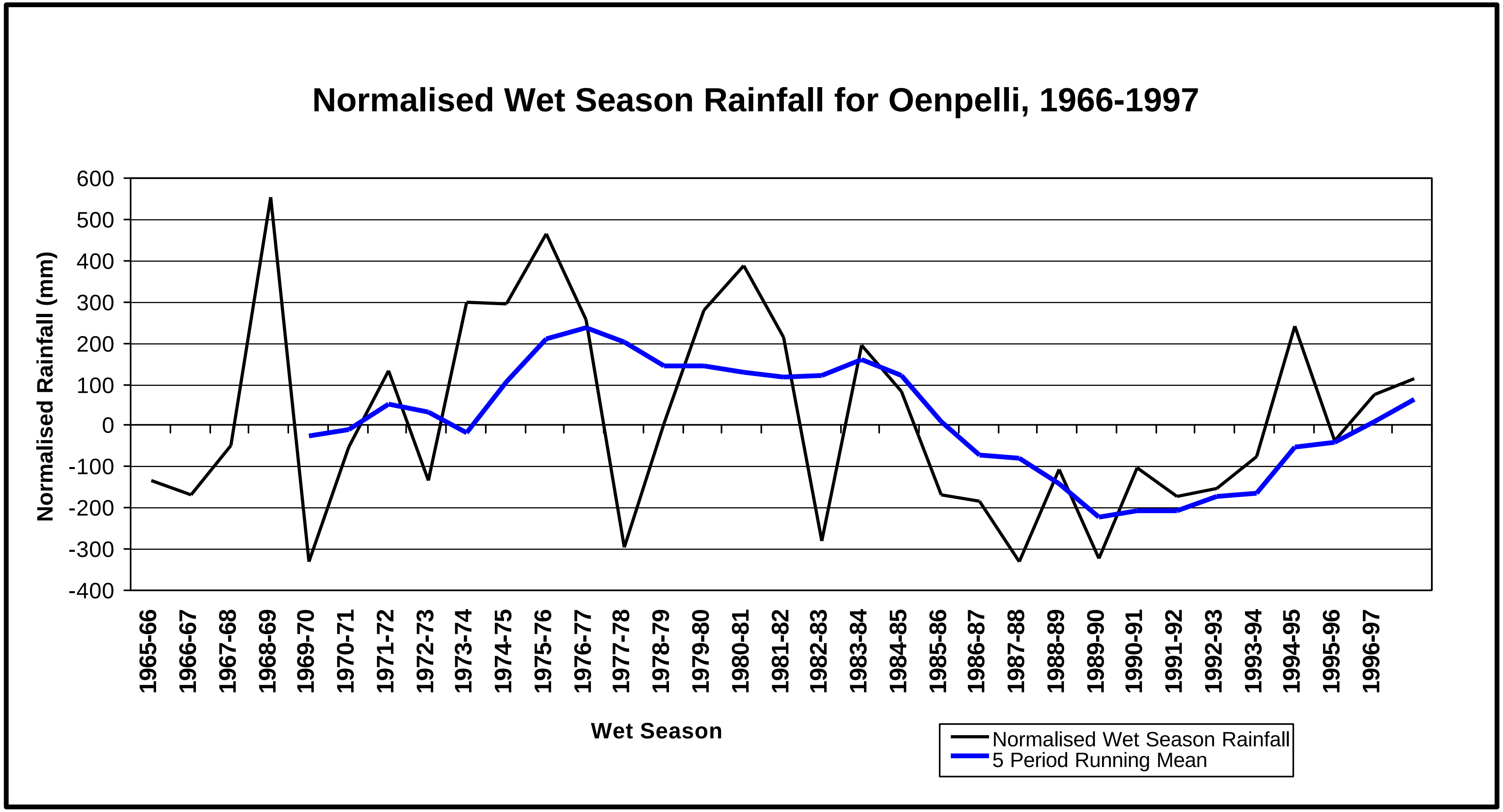

Figure 4.5 Normalised Wet Season Rainfall for Oenpelli, 1966-1997

A five period running mean is applied to the normalised Wet season rainfall, for the months November to March.
(Source: Raw data were obtained from the Bureau of Meteorology in Darwin)

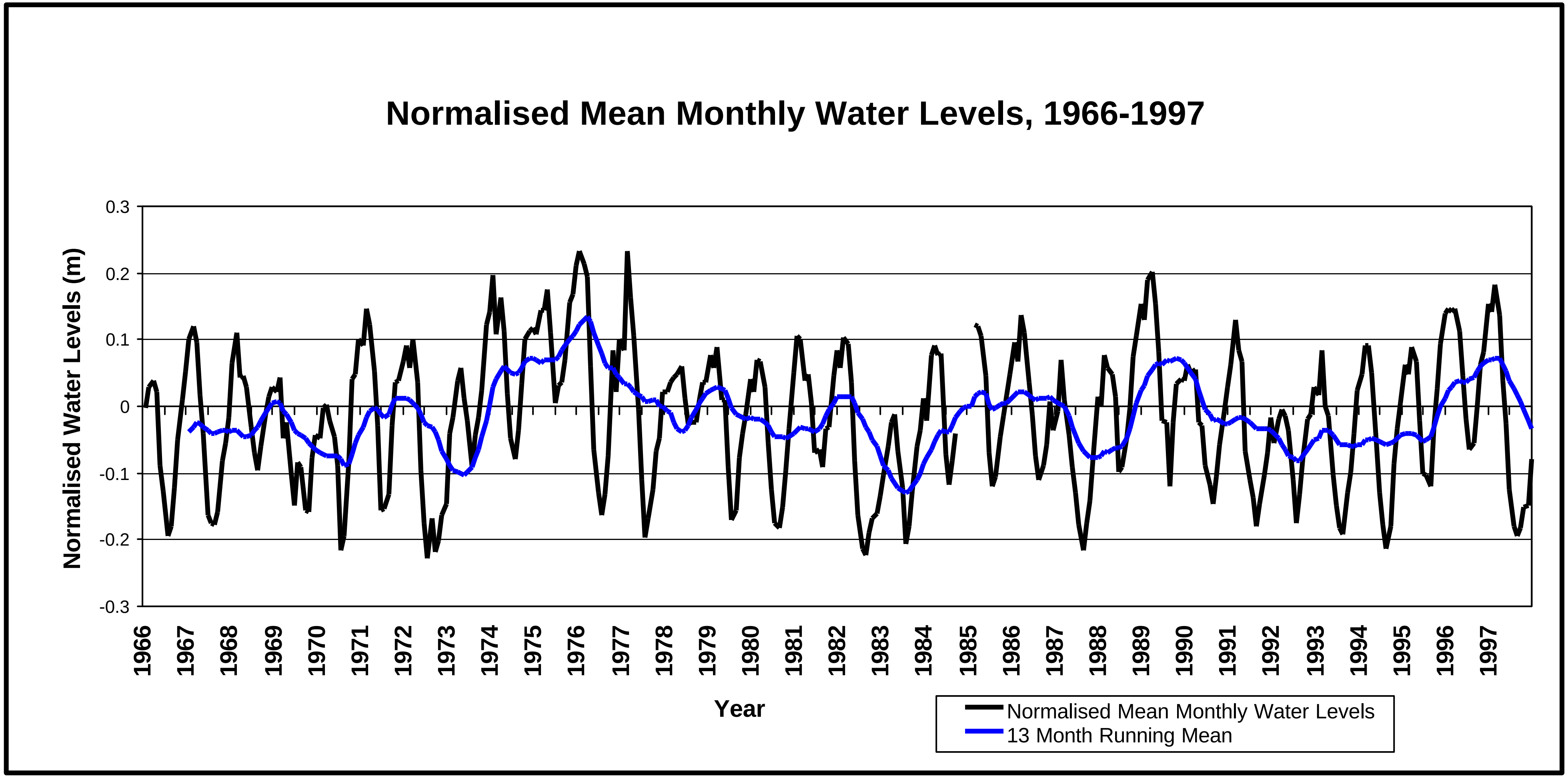

Figure 4.6 **Normalised Mean Monthly Water Levels for Darwin, 1966-1997**
A thirteen month moving average is applied to the normalised mean monthly water levels for Darwin between 1966-1997.
(Source: Raw data were obtained from the National Tidal Facility in Adelaide)

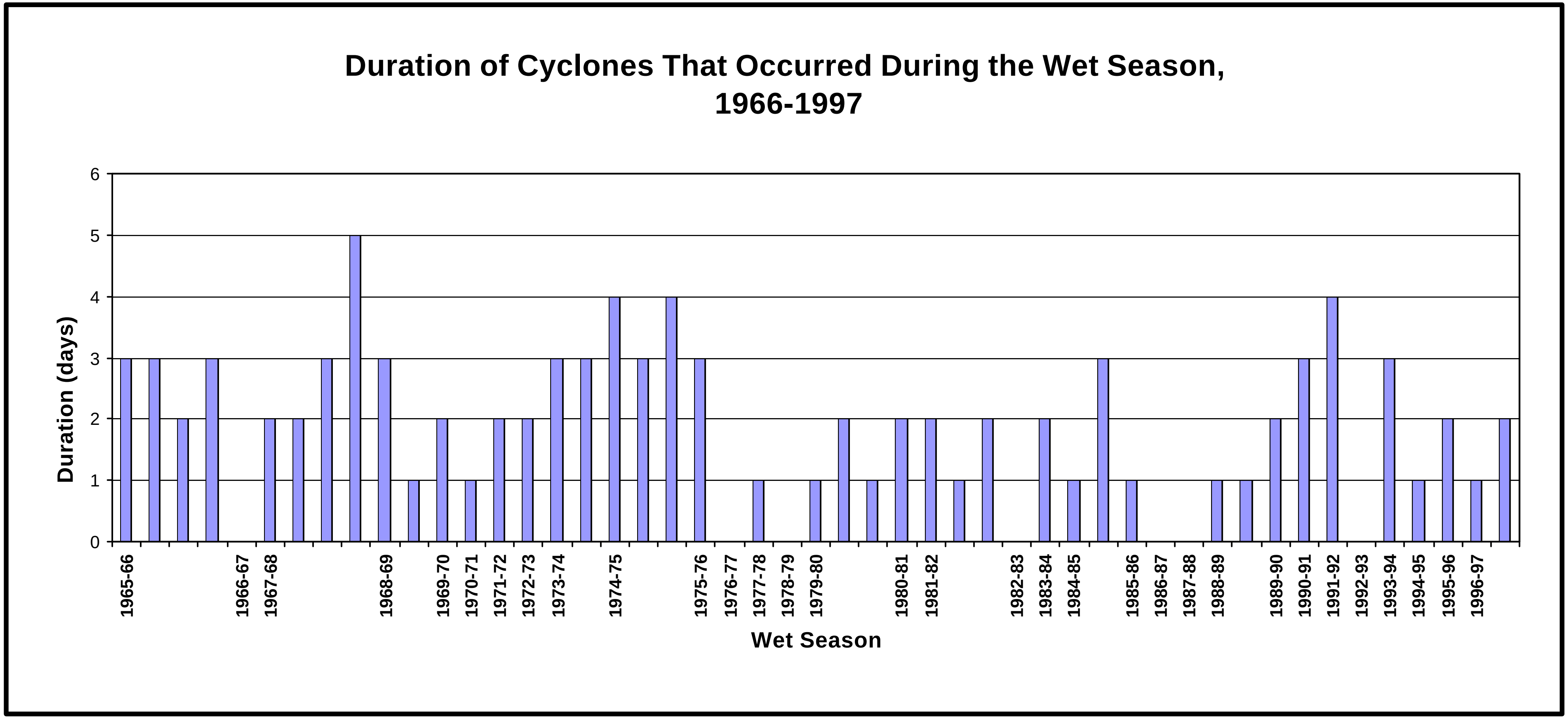

Figure 4.7 **Duration of Cyclones that Occurred During the Wet Season Between, 1966-1997**
The number of cyclones that occurred during the Wet season, from November to March, is shown along with their duration. (Source: Raw data was obtained from the Bureau of Meteorology in Darwin)

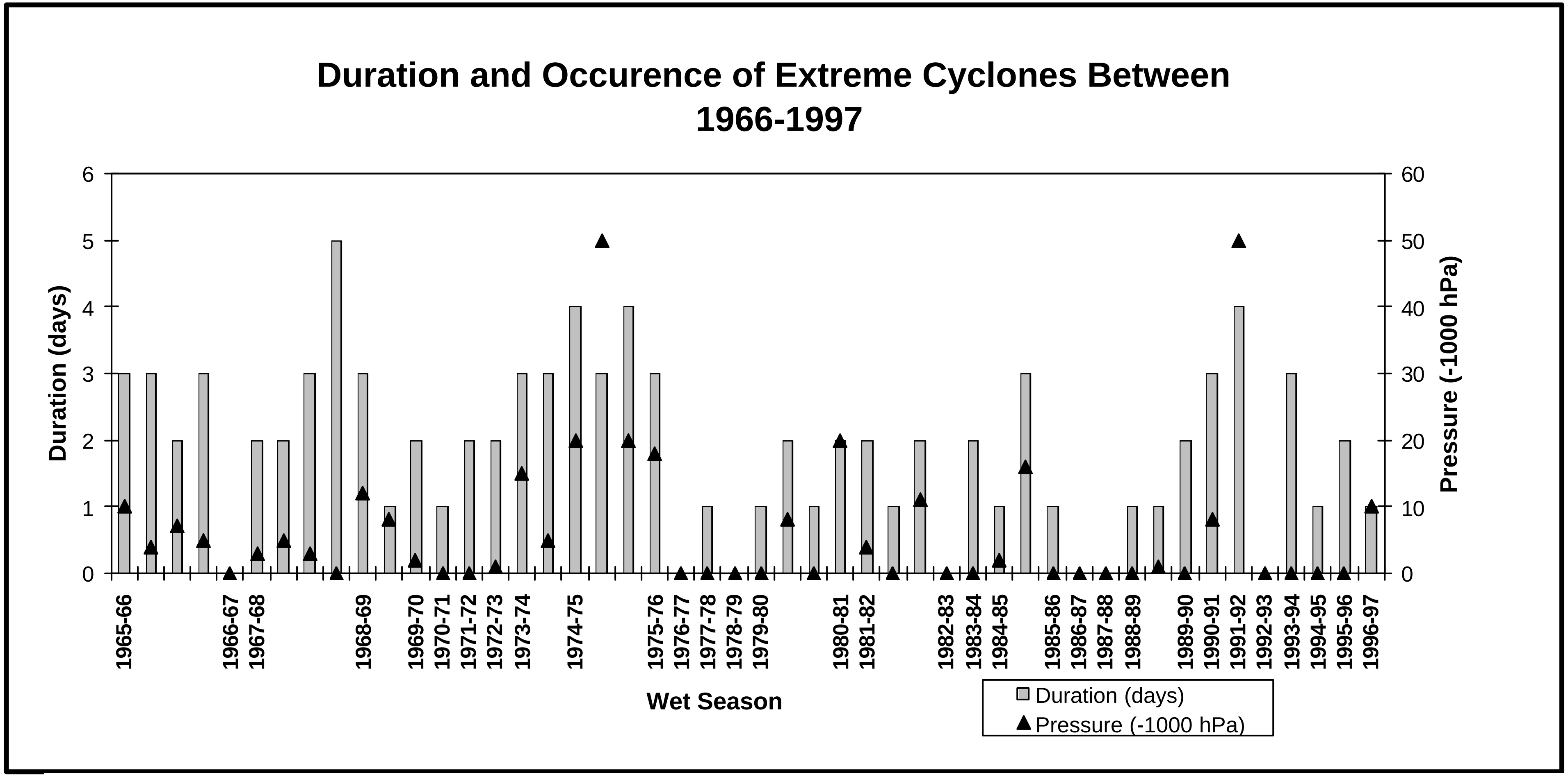

Figure 4.8 Duration and Occurrence of Extreme Cyclones that Occurred During the Wet Season, 1966-1997
The duration, occurrence and pressure difference of cyclones less than 1000 hPa is shown. These cyclones were considered to be extreme. (Source: Raw data were obtained from the Bureau of Meteorology in Darwin)

CHAPTER 5: DISCUSSION AND CONCLUSIONS OF MORPHOLOGICAL CHANGE AT POINT FAREWELL

5.1 Introduction

The study area at Point Farewell was selected as a case study to document past and present morphological changes associated with saltwater intrusion. The contemporary morphology at Point Farewell was described from 1997 aerial photographs and ground-truthed in 2001. A morphological map was constructed to illustrate the units and sub-units associated with the salt-affected site. Processes initiated by saltwater intrusion and currently contributing to morphological change were determined from information collated from aerial surveys, field observations and laboratory analyses. Morphological changes that have occurred since saltwater intruded the freshwater basin was reconstructed from each set of the available aerial photographs (1950, 1975, 1984 and 1997). A series of morphological maps was created to illustrate the morphological changes associated with saltwater intrusion. Contemporary and historical datasets have been analysed in conjunction with climatic and oceanographic data to determine the conditions that promoted rapid saline intrusion and morphological change at Point Farewell.

5.2 Contemporary Morphological Change at Point Farewell

One of the broader aims of this thesis was to characterise the contemporary morphology of a salt affected site and identify processes active within the area. Seven main morphological units and a number of sub-units were recognised. The small-scale investigation and large-scale systems approach used to describe and characterize the morphology at Point Farewell revealed much complexity. Several processes were observed to be currently active within the area and appear to be contributing the morphological change. They are; (1) saltwater intrusion, (2) freshwater retention, and (3) aeolian transport processes. These are briefly described below and their broader implications for changes occurring within the Alligators Rivers Region are discussed.

Saltwater intrusion has directly and indirectly altered the morphology at Point Farewell. The direct impact of saltwater intrusion has been the headward extension and expansion of the tidal creek that initially enabled saltwater to invade the freshwater basin. Evidence of this process is revealed in the contemporary morphology, specifically on the Lower Coastal Plain. The sub-units associated with the tidal creek represent the progressive development of the tidal creek network. This characterisation extends the research of Knighton *et al.* (1992) by providing a classification of morphological units, which are readily identifiable in the field for each phase of development.

The process of tidal creek expansion is currently active on the lower coastal plain. The lower coastal plain lies below the level of high spring tides and is thus subject to tidal flooding and surface invasion of saltwater on a fortnightly basis. Tidal splays are left where surface invasion and subsequent scour and deposition of sediment takes place over the coastal plain during high tides. Tidal splays are the initial stage of tidal scour and channel incision. Over a longer period of time, and with progressive tidal action, tidal channels begin to widen and deepen, lengthen and bifurcate, forming tidal creek tributaries. Tidal fans become apparent and represent the stage of channel formation and development. The evolution of the tidal creek network on the lower coastal plain as indicated by the sequential development of tidal splays and fans may serve as an analogy for the broader pattern of saltwater intrusion currently active within larger catchments of the Alligator Rivers Region.

The process of freshwater retention and subsequent recovery from saltwater intrusion is contained within the freshwater basin. Revegetation of the floodplain by grasses that are usually found in freshwater environments and recolonisation of *Melaleucas* within areas of *Melaleuca* dieback are apparent signs of recovery. However, at Point Farewell this may only be temporary given that the tidal creek is now outflanking the barrage. Also, signs of recovery may be a result of the large Wet season rainfall experienced in the last two years (Plate 5.1). The processes currently active within the freshwater basin illustrate that a delicate balance exists between freshwater and saltwater regimes and that only a small change is required to shift the balance.

Plate 5.1 Point Farewell in Flood

The basin was holding large amounts of freshwater following the 1997-1998 Wet season. This was well above average and was exceeded by the 1999-2001 Wet seasons. The large influx of freshwater may have facilitated the recolonisation of *Melaleuca* species in areas of *Melaleuca* dieback.

There also appears to be a close relationship between saltwater intrusion and aeolian transport processes currently active within the Lower Coastal Plain. The expansion of the tidal creek network on the Lower Coastal Plain has been facilitated by the lack of resistance from vegetation and surface lowering through deflation of sediment during the Dry season. In turn, surface lowering promotes favourable conditions for continued expansion of the tidal creek. This raises an interesting question of whether sediment compaction and/or sediment deflation has promoted favourable conditions for tidal creek network development on the coastal plain within the Alligators Rivers Region. Woodroffe and Mulrennan (1993) suggested that compaction and consolidation of sediments since their deposition has lead to lowering of the coastal plains below spring high tide level. However, the process of saltwater intrusion has only been evident in the last 50 years and thus may not be a rapid response to long-term change in geomorphology of the coastal and estuarine floodplains.

5.3 Historical Morphological Change in Response to Climatic and Oceanographic Conditions

The contemporary morphology described above is dramatically different to the morphology of the study site in 1950. Since 1950 the study site has undergone significant morphological change. The most apparent is that associated with saltwater intrusion. The question that needs to be addressed is what were the conditions driving the rapid landward extension and expansion of the tidal creek and subsequent morphological change apparent in the aerial photography. The outcome from the preliminary analysis of climatic and oceanographic data reveals that the answer lies within reconstructing the conditions experienced during 1950 and 1997.

Since there are no permanent tide gauges in the Van Diemen Gulf waters, water levels recorded in the Darwin Harbour were used. This record is a poor surrogate for fluctuations in water levels experienced in the Van Diemen Gulf given that Darwin is located outside the Gulf. However it is the best available data at present. Also, due to the incomplete climate coverage in the Region and the relatively short climatic records, the closest rainfall station to the study site was located at Oenpelli, 55 km south-east of Point Farewell. Hence, the rainfall data for Oenpelli were used as an estimate of rainfall experienced at Point Farewell. The lack of permanent tide gauges and incomplete climate coverage for the region may be reasons why climatic and oceanographic processes have until now been neglected and saltwater intrusion has been attributed to other factors. However, the preliminary analysis does enable reasonable inferences to be made regarding the potential processes responsible for the past morphological changes.

5.3.1 Progress of Saltwater Intrusion, 1950-1997

Between 1966 and 1975, monthly rainfall progressively increased and a high frequency of low intensity cyclones was experienced during the Wet season. Wet season rainfall was well above average between 1973-1975 (Figure 5.4) prior to when the aerial photography was flown and the frequency of cyclones progressively increased (Figure 5.3). This coincided with above average water levels that appear to have increased since mid-1973. Total network growth was plotted against normalised mean monthly water levels (Figure 5.1) and normalised monthly rainfall (Figure 5.2) experienced between 1950-2001. Although a slow rate of network growth was experienced between 1950 and 1975, the expansion and extension of the tidal creek was progressively increasing (Figures 5.1 and 5.2).

It was apparent in the 1975 aerial photography that flood channels had breached the likely buffer zone between the freshwater basin and the headward extent of the tidal creek. Consequently the low-lying basin was made vulnerable to tidal processes. The progressive increase in above average Wet season rainfall implies that the Wet season floods were probably responsible for breaching the buffer zone. The increased frequency in cyclones that occurred during the Wet season coincided with the increased water levels during 1973-1975 (Figures 5.1 and 5.3).

Additionally, the Wet season is conducive to the formation of tropical cyclones. If the cyclones act in an onshore direction, they generate high water levels associated with storm surge, which have a capacity to elevate water levels in the Gulf and drive saltwater landward. Cyclone Tracey occurred several months prior to the 1975 aerial photography. The cyclone generated a surge of up to 4 m in Darwin. Any increase of water levels in the Gulf of this magnitude would have facilitated the expansion and headward extension of the tidal creek network. In turn, this would have facilitated the invasion of saltwater into the freshwater basin, as is apparent in the 1975 aerial photography.

The most rapid period of landward extension of the tidal creek occurred during 1975 and 1985 (Figures 5.1 and 5.2). During this time period, 50% above-average mean-monthly water levels were experienced but were only half the height than those that occurred during 1966-1975. Also, the yearly trend indicated a progressive decline in water levels (Figure 5.5). Wet season rainfall events were well above average but progressively declined following the 1976-1977 Wet season (Figure 5.6). A low frequency of low intensity cyclones was experienced during this time period.

The above conditions have significant implications regarding the rapid tidal creek extension that occurred between 1975 and 1984. Wet season floods may have accentuated channel incision as suggested by Knighton et al. (1992) for the Lower Mary River Plains and also acted to force saltwater out of the system. This may have initially counteracted the rising water levels and possible storm surges associated with cyclonic activity. It is one reason why network growth was relatively slow during 1950 and 1975. However, Wet season rainfall and thus flood events declined following 1976-1977. Surge events coincidental with a drier than average Wet season are likely to be conducive to saltwater intrusion. Such conditions may occur in the Wet seasons with a low incidence of tropical cyclones or drier conditions occurring in association with tropical cyclones afflicting the western part of the Van Diemen Gulf. Hence, low frequency and low intensity cyclonic events and above average water levels provide favourable conditions for channel cutting given the limited opposing force of Wet season floods.

Between 1984 and 1997 there was an apparent slowing of the rate of tidal creek extension (Figures 5.1 and 5.2). This coincided with moderate fluctuations in monthly rainfall and mean monthly water levels (Figures 5.1 and 5.2). Low frequency cyclones of low intensity were experienced during the Wet seasons. Hence conditions appeared to have stabilized allowing the system to gradually achieve a new dynamic equilibrium between freshwater and tidal regimes during this period.

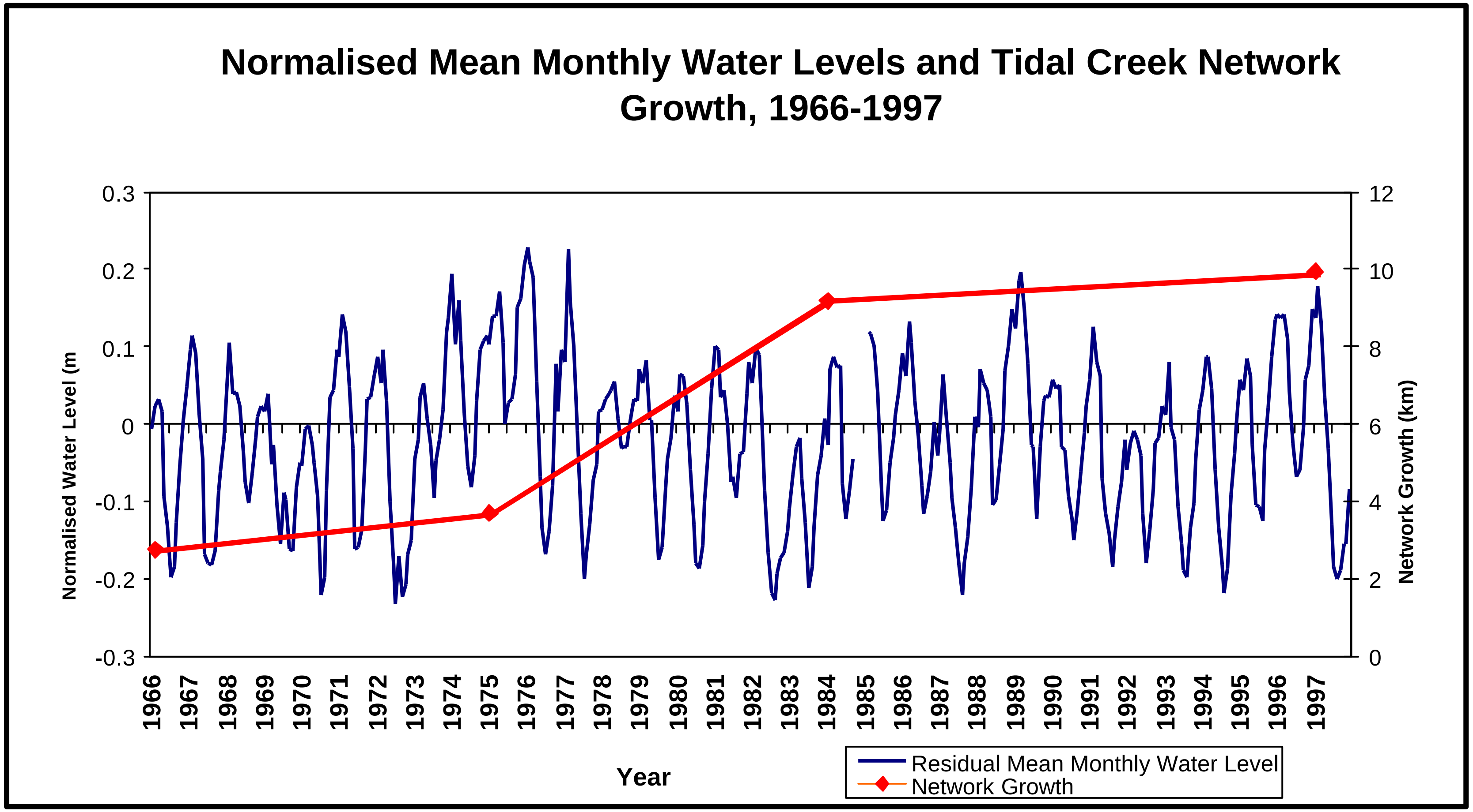

Figure 5.1 Normalised Mean Monthly Water Levels in Darwin Harbour and Tidal Creek Network Growth, 1966-1997

The network growth of the tidal creek between 1966 and 1997 is overlayed with the normalised mean monthly water levels.

(Source: Mean monthly water level data for Darwin were obtained from the National Tidal Facility in Adelaide)

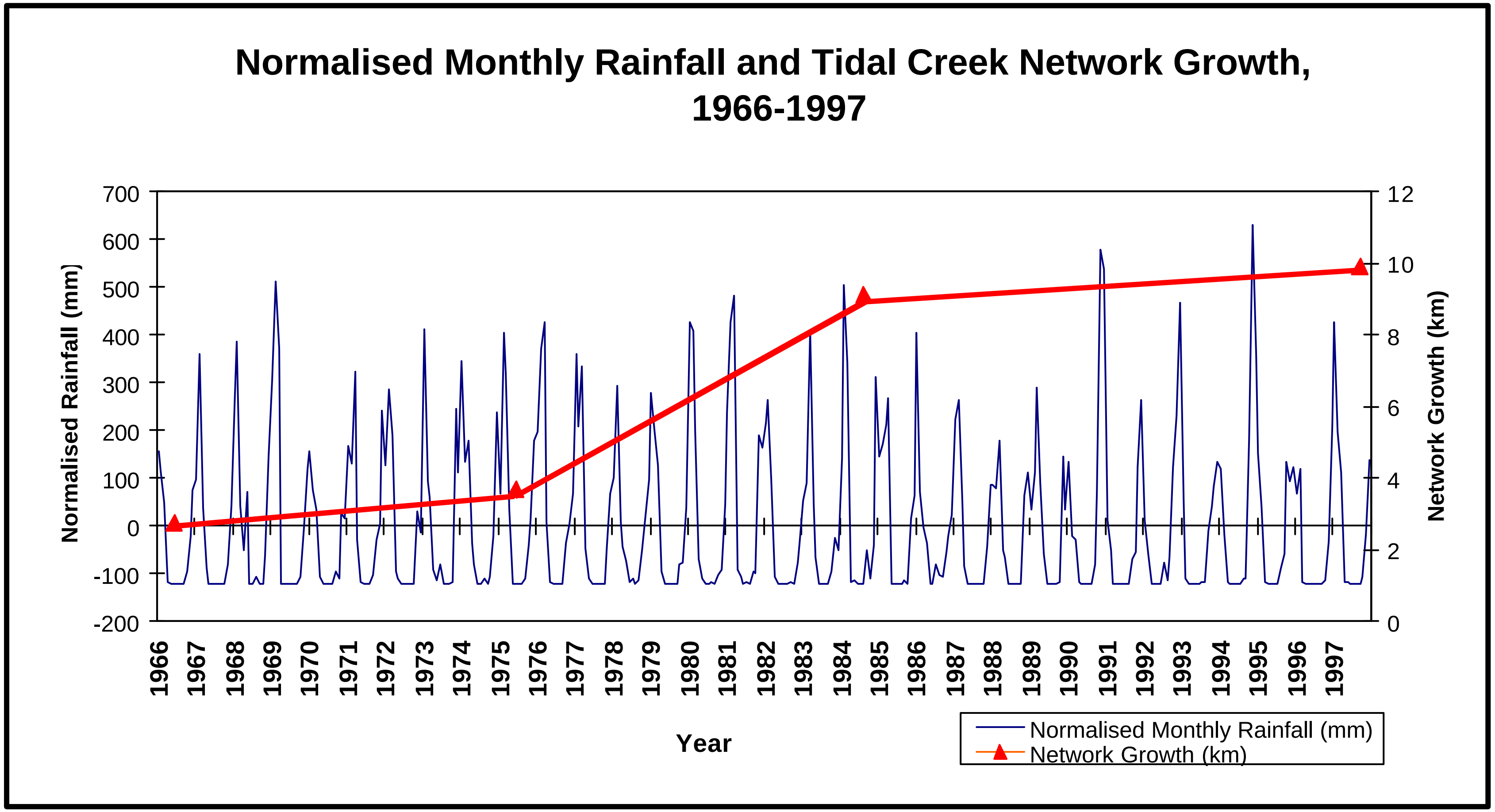

Figure 5.2 **Normalised Monthly Rainfall for Oenpelli and Tidal Creek Network Growth, 1966-1997**

The network growth of the tidal creek between 1966 and 1997 is overlayed with the normalised monthly rainfall for Oenpelli.

(Source: Monthly rainfall data for Oenpelli were obtained from the Bureau of Meteorology in Darwin.)

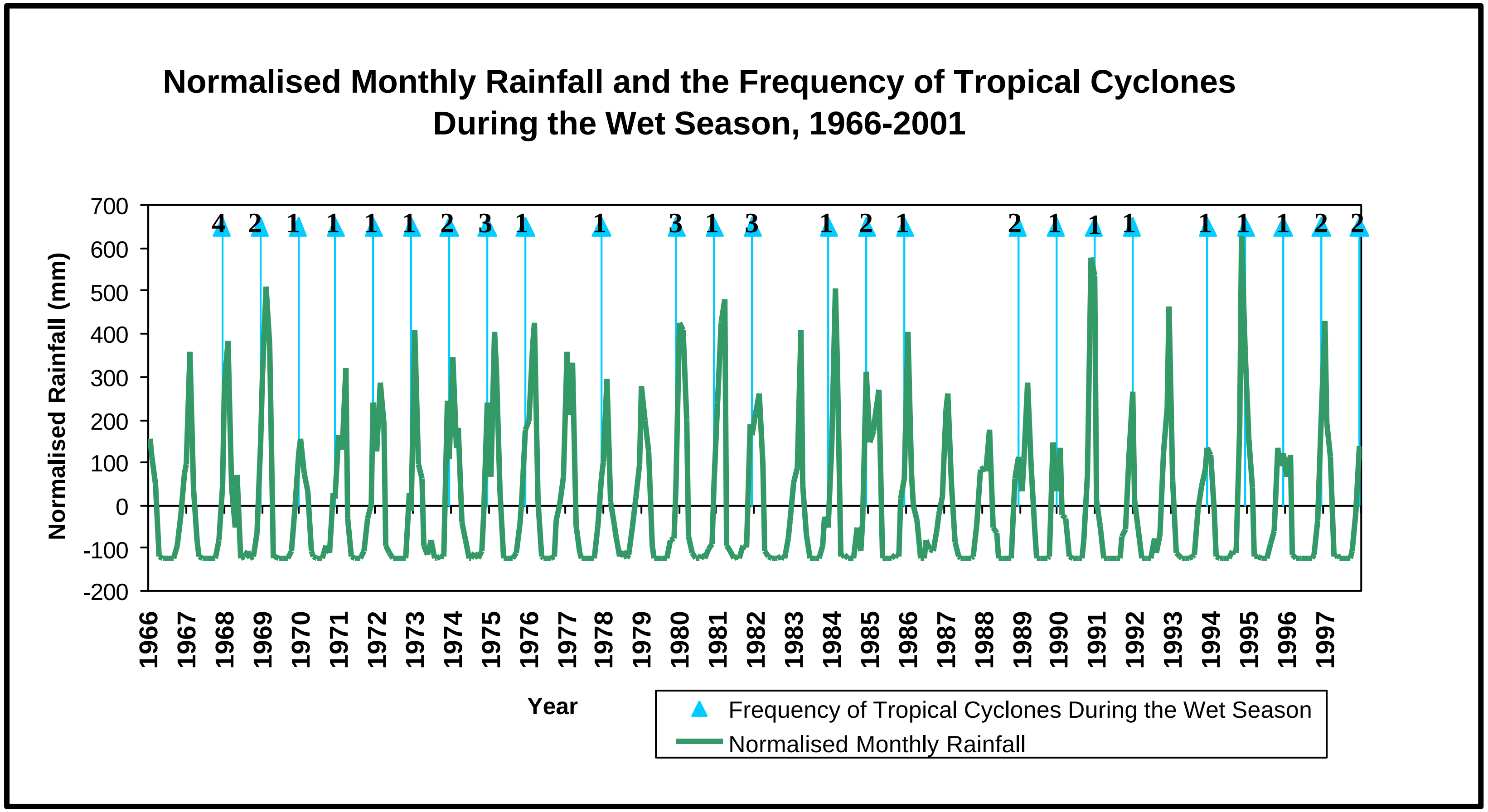

Figure 5.3 **Normalised Monthly Rainfall and the Frequency of Tropical Cyclones During the Wet Season, 1966-1997**

The number of cyclones that occurred during the Wet season in the Northern Territory were determined and overlayed with the normalised monthly rainfall for Oenpelli.

(Source: Data were obtained from the Bureau of Meteorology in Darwin.)

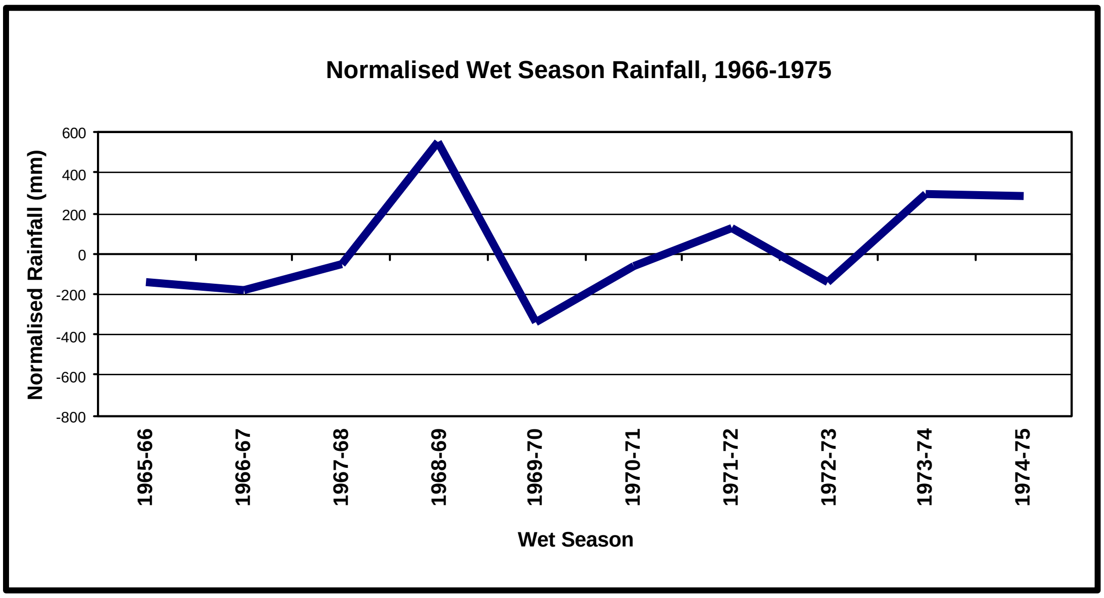

Figure 5.04 Normalised Wet Season Rainfall for Oenpelli, 1966-1975
(Source: Raw data were obtained from the Bureau of Meteorology in Darwin.)

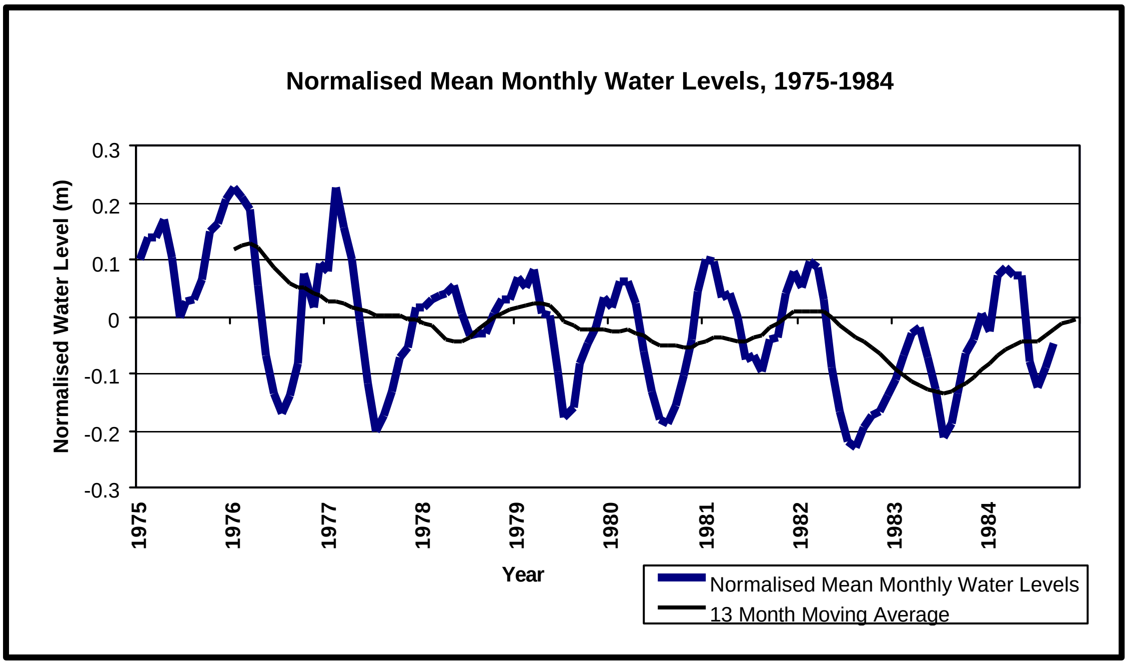

Figure 5.05 Normalised Mean Monthly Water Levels for Darwin Harbour, 1975-1984
(Source: Raw d ata were obtained from the National Tidal Facility in Adelaide.)

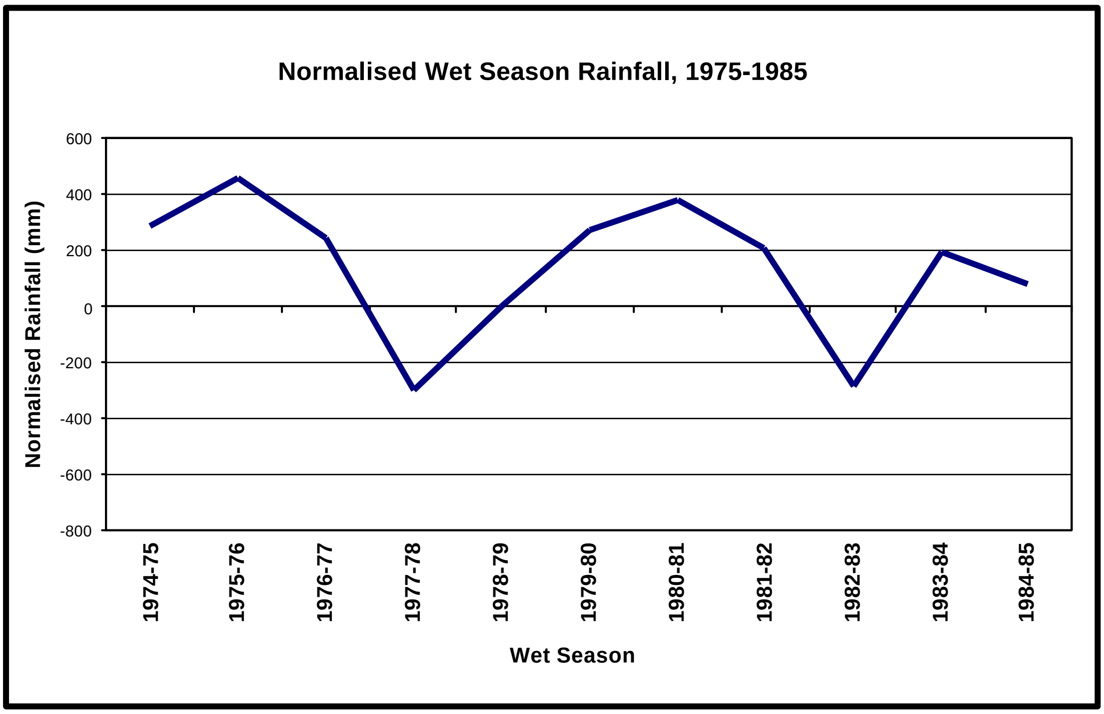

Figure 5.06 Normalised Wet Season Rainfall for Oenpelli, 1975-1985
(Source: Raw data were obtained from the Bureau of Meteorology in Darwin.)

5.3.2 Morphological Response to Saltwater Intrusion

Saltwater intrusion into the freshwater basin, apparently driven by climatic and oceanographic conditions experienced between 1950 and 1997, has resulted in significant morphological change as summarised in Table 5.1. Much of the change can be attributed to the process of saltwater intrusion. However other processes, such as freshwater retention and aeolian sediment processes, have also been significant.

Saltwater intrusion into the freshwater basin appears the direct consequence of the breakdown of a natural barrier that was present in 1950. At that time, the freshwater basin was buffered by the headward extension of the developing tidal creek by an area of alluvial deposition that would have functioned as a natural levee bank. The above-average Wet season rainfall experienced prior and during the 1975 aerial photography resulted in the breaching of the barrier by flood channels. Wet season floods facilitated barrier breakdown and tropical cyclone storm surge events associated with tropical cyclones enabled rapid saltwater intrusion into the freshwater basin.

Table 5.1 Morphological Changes at the Study Site, 1950-1997

Feature	1950-75	1975-84	1984-97	Gross Change
Landward Extension of Main Tidal Creek	0.075 km	0.075 km	4.05 km	4.2 km extension
Landward Extension of Developing Tidal Creek	1.05 km	2 km	Distinct channels not visible from aerial photographs	3.05 km extension
Total Network Growth	2.8 km	5.5 km	0.75km	9.05 km growth
Vegetation Saline Mudflat on the Coastal Plain	41% loss	Further 65% loss	15% increase	43% loss
Unvegetated Saline Mudflat on the Coastal Plain	906% increase	Further 44% increase	26% reduction	975% increase
Melaleuca Forest	45% loss	Further 26% loss	Further 7% loss	64% loss

The expansion of the tidal creek network was most extensive on the Lower Coastal Plain. The low gradient of the plains and the presence of palaeochannels facilitated network development. However, surface lowering by aeolian sediment transport processes appears to have been an influencing factor. The surface invasion of saltwater associated with the developing tidal creek results in the loss of vegetation. The increase in bare saline mudflat and lack of vegetation to stabilise the surface makes it susceptible to wind erosion, particularly in the Dry season when mudflat dries to desiccation. This process was active during ground-truthing in 2001 and may have been active in the past, promoting favourable conditions for network expansion.

Channel incision and extension into the freshwater basin was rapid following 1975 and allowed for the rapid drainage of freshwater from the basin between 1975 and 1984. Although Wet season floods accentuate channel incision, they also act to force saltwater out of the system. The loss of *Melaleuca* forest may therefore have resulted from the lack of freshwater retention rather than saltwater intrusion given that *Melaleuca* species, specifically *Melaleuca cajuputi* and *Melaleuca viridiflora* are salt-adapted species (Lynch, 1997). This further emphasises the complexity of the natural system.

Morphological changes that occurred between 1985 and 1997 were not as extensive as between 1950 and 1985, indicating that the system was slowing achieving a new equilibrium between freshwater and tidal regimes. The construction of the barrage may have interfered with and offset morphological change to some extent. However, climatic and oceanographic conditions experienced during this period were moderately stable in contrast to the previous time periods. Thus, the limited morphological change is more likely attributed to the moderate climatic and oceanographic conditions experienced than to construction of the barrage.

5.4 Conclusions

The aims of this thesis were to (1) characterise the contemporary morphology at Point Farewell, a salt affected site in the Alligators Rivers Region; (2) describe the recent morphological changes that have taken place since saltwater invaded the freshwater basin; and (3) identify the potential processes contributing to the recent change. The contemporary morphology has been mapped from the 1997 aerial photographs and ground-truthing in 2001. The morphological units and their associated sub-units represent the direct and indirect impacts of saltwater intrusion. Documentation of processes currently contributing to morphological change revealed much complexity. Saltwater intrusion through expansion of the tidal creek on the Lower Coastal Plain has facilitated loss of vegetation and subsequent deflation of sediment following sediment desiccation in the Dry season. This was a significant finding as prior to this research saltwater intrusion through extension and the expansion of tidal creeks have been attributed to surface lowering by compaction and consolidation of sediments over long periods of time (Woodroffe and Mulrennan, 1993). It raises an interesting question of whether surface lowering through wind erosion might be related to continued expansion of tidal creeks since 1950 at Point Farewell and the Alligator Rivers Region in general.

This research has demonstrated the viability of using a time series of aerial photography for identifying morphological change over time. Aerial photographs offered colour and textural information and enabled discrimination of morphological units and their subsequent change over time. In addition, stereoscopic viewing of the three-dimensional structure of terrain and vegetation allowed further interpretation. Saltwater intrusion and consequent morphological change over time has apparently been driven by climatic and oceanographic conditions experienced during the time span of the aerial photography. It appears to be related to threshold-exceeding events such as Wet season floods, stronger than average monsoonal activity, storm surges and very high tides.

This research has implications for management of saltwater intrusion given the construction of a barrage in 1995. It appears that erosion of the barrage and its potential bypassing by tidal creeks is strongly influenced by climatic and oceanographic conditions. The limited success of the barrage may be attributed to the climatic and oceanographic events that occurred since 1997. Regardless of the exact conditions that were responsible for the failure of the barrage it appears to be an ineffective management solution. This research has shown that saltwater intrusion is a natural process related to threshold-exceeding climatic and oceanographic conditions and the natural physiography of the area. Therefore to prevent salinisation of the coastal plain and associated freshwater wetlands may be impracticable. Physical environments are dynamic environments that are always subject to change. Perhaps landowners and managers should accept the change.

5.4.1 Future Research and Monitoring

This research has provided a baseline study for more detailed monitoring of saltwater intrusion and subsequent morphological change. Future research should incorporate further analysis of the climatic and oceanographic data, as well as determination of a storm-surge history for the region. Determination of which past cyclones and other meteorological conditions produced surge events conducive to saltwater intrusion would allow more insight into the processes driving morphological change at Point Farewell and the Alligator Rivers Region. This could be achieved by analysing the path of cyclones and their associated wind conditions over the last 50 years. However, more detailed investigations are required which can only be achieved through improved monitoring of climatologic and oceanographic conditions occurring in the Van Diemen Gulf. This is important in light of predicted future climate and sea level change as future replication of conditions experienced during 1950 to 1997 will result in similar morphological changes before a new dynamic equilibrium between freshwater and tidal regimes is achieved.

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APPENDIX A

GIS Methodology

APPENDIX A GIS METHODOLOGY

A detailed account of the GIS methodology used in this research is outlined below. The main GIS techniques employed were: (a) image-to-image registration to geo-reference and mosaic the aerial photographs, and (b) 'heads-up' digitizing in Arc View for the construction of morphological maps. Most of the explanations offered in this section were taken from the Arc Info and Arc View Help Documentations. Please refer to these if you require any further information on the processes and commands used.

(A) Image to Image Registration

First, a mosaic of fourteen 1997 aerial photographs was created within a GIS environment using image-to-image registration. This was used as the base image to register the aerial photographs for the years 1950, 1975 and 1984 to the same working scale of 1:15,000. Due to the lack of common features between 1950 and 1997, image registration was sequential where the 1984 aerial photographs were registered to 1997 mosaic, then 1975 to 1984 and finally 1950 to 1975. The methods outlined below appear in the same order they were applied and are illustrated in Figure App-1. The errors and problems associated with particular methods are also discussed.

1. Scan aerial photographs

Each aerial photograph was scanned (350dpi) and saved as an uncompressed TIFF file. Details of aerial photographs used are summarized in the Table App-1.

2. Create a workspace

A workspace was created within the Arc Info environment using the command **Arc: cw z:/ptfarewell**. The command used to move into the workspace was **Arc: w z:/ptfarewell**.

3. Create Point Coverage of Artificial Tic Points

There were no coverages to georeference each set of aerial photographs to real-world co-ordinates. Hence, images were registered using artificial tic points. Common features between each image were used as artificial tic points for registration. Shape files representing the common features were created in Arc View. Each shape file consisted of at least 15 points to increase accuracy of registration. This was only possible when creating shape files to register images of the same date. However, due to a lack of common features between dates, only a small number of points (less than 10) could be used as artificial tic points. Shape files were then converted to point coverages in Arc Info using the SHAPEARC command:

Arc: shapearc points97a.shp points97a.

4. Register Images

The REGISTER command was used for the image-to-image registration, where an image was registered to a specific point coverage created from common features of the second image:

Arc: register pf003.tiff points97a 2 composite # # # point.

The register command initiates an interactive program that allows you to create a world file by graphically choosing from (image) and to (coverage) points. The following steps were used to register each image.

(a) The first step was to establish a viewing area with the image and coverage windows. The view boxes were moved in order to identify the correct viewing area.

(b) Once the viewing area was established, **Redraw Overlay** was selected from the **View** pulldown menu of the **Links Action** menu in order to draw the overlay, which displayed to areas selected in the image and coverage windows.

(c) Links were added interactively using the cursor by left clicking on the image feature which became the 'from' point and then left clicking on the corresponding point which became the 'to' point. In order to create accurate links. The view boxes in the image and coverage windows were continuously resized to zoom in on specific locations, using the right button (NT version). The links (from and to points) were continuously added from all over the image by moving and resizing the view boxes in the Image and Coverage windows.

(d) When all the links were added, Link Actions was selected from the View pulldown menu and Register was selected to evaluate the accuracy of registration.

(e) The links with high RMS error, greater than 1.5 were deleted. In general RMS error should not be greater than 2 for accurate registration. The RMS errors were all below 1.5.

(f) The final links were saved before quitting out of the program.

5. Rectify images

Each registered image was then rectified using the RECTIFY command in the Arc environment e.g. **Arc: rectify pf003 final003**. The RECTIFY command creates a new rotated, scaled and transformed image based on the parameters in the world file.

(B) Construction of Morphological Maps

Morphological maps were constructed from the image mosaics for each year by ‘heads up’ digitising in Arc View. This involved creating a polygon shape file, representing the morphological units and their associated sub-units for each year. Boundaries of morphological units and associated sub-units were digitized using the mouse. Once all units and sub-units had been digitized, polygons that comprised the same unit or sub-unit were assigned a common value by adding a new field to the polygon attribute table. Features were then dissolved according to common attributes using the Geo-Processing wizard. Finally, layouts of the morphological maps were then created in Arc View.

Table App-1 Details of Aerial Photography

YEAR	MONTH	RUN #	PHOTO #	SCALE	SOURCE
1950	16/5	3	5082	1:25000	*eriss*
1950	16/5	2	5042	1:25000	*eriss*
1975	7/5	4	3792	1:12500	PAN
1975	7/5	4	3769	1:12500	PAN
1984	13/8	52	9504	1:12500	PAN
1984	13/8	51	9466	1:12500	PAN
1984	13/8	51	9467	1:12500	PAN
1997	20/10	10	003	1:5000	*eriss*
1997	20/10	10	005	1:5000	*eriss*
1997	20/10	10	007	1:5000	*eriss*
1997	20/10	9	036	1:5000	*eriss*
1997	20/10	9	037	1:5000	*eriss*
1997	20/10	9	038	1:5000	*eriss*
1997	20/10	9	039	1:5000	*eriss*
1997	20/10	9	041	1:5000	*eriss*
1997	20/10	9	042	1:5000	*eriss*
1997	20/10	9	049	1:5000	*eriss*
1997	20/10	8	005	1:5000	*eriss*
1997	20/10	8	051	1:5000	*eriss*
1997	20/10	8	052	1:5000	*eriss*
1997	20/10	8	053	1:5000	*eriss*

eriss = The Environmental Institute of the Supervising Scientist

PAN = Parks Australia North

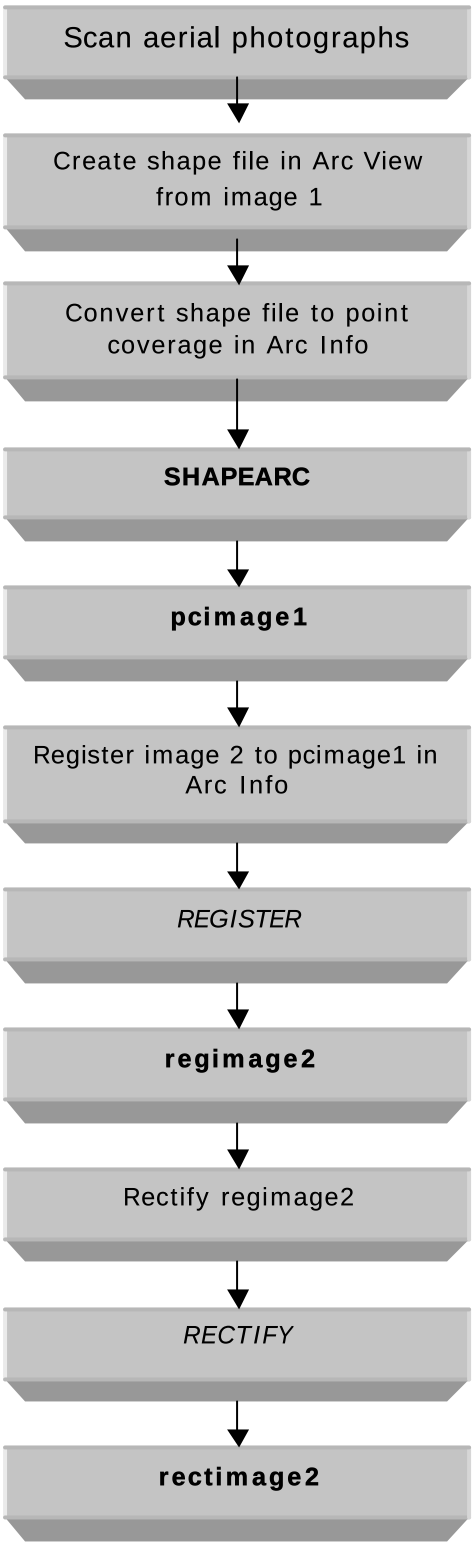

Figure App-1 Example of Image-to-Image Registration and Rectification
The flow chart illustrates the steps taken to register and rectify the aerial photography. The words in italics represent the commands used to generate the output, which is in bold. The words in regular font briefly describe the processes used to generate the output at each step.

APPENDIX C

Literature Review

A Review of the Research on the Evolution and Hydrodynamics in the Alligator Rivers Region

Table of Contents

A Review of the Research on the Evolution and Hydrodynamics in the Alligator Rivers Region

ABSTRACT

Extensive geomorphic research on the evolution and hydrodynamics of the estuaries and coastal plains has been undertaken in Alligator Rivers Region. This has provided much insight into past and present changes, however several shortcomings have been identified. Poor climate coverage, insufficient climatic records and limited data on wet season hydrology have made it difficult to model hydrodynamic processes. The development of a one-dimensional non-linear model by Vertessy (1990) has improved the current understanding on tidal hydrodynamics in the estuaries. Stratigraphic analysis, supported by radiocarbon dating, has allowed identification of three broad phases of estuarine infill and coastal plain development during the Holocene. Investigations into more recent changes that have occurred in the region are lacking. Consequently, the contemporary processes responsible for change are largely unknown. This paper reviews the available research on the evolution and hydrodynamics that has been undertaken in this region. This is achieved by outlining the principle findings of the research and assessment of the strengths and weaknesses of each study. Based on this critical assessment, recommendations are made regarding the direction of future geomorphic research in the Alligator Rivers Region.

INTRODUCTION

The aim of this paper is to review the geomorphic research pertaining to the evolution and hydrodynamics of the tidal rivers and coastal plains of the Alligator Rivers Region (ARR).

The Alligator Rivers Region is a highly dynamic environment that has changed dramatically since the Holocene. This time period is most relevant with respect to providing insight into future changes, in light of global warming and predicted sea level rise. This is one of the main reasons why detailed investigations have been focused on the Holocene development of estuarine reaches of the tidal rivers and coastal plains. However, contemporary research on more recent changes in the region is lacking. This is a major shortcoming of the research undertaken in the ARR, along with several others, which will be outlined in this paper.

There has been much research into the hydrodynamics of the estuaries and coastal plains in the ARR. These studies are important, given that interaction between tidal and fluvial forces play a significant role in estuarine morphodynamics (Chappell, 1988). Knowledge of hydrodynamic processes in the estuarine reaches of the rivers in the ARR is integral to understanding the process of saltwater intrusion, which has become a major coastal management problem (Cobb *et al.*, 2000). The hydrodynamics of the ARR is incompletely defined. Research on the hydrodynamics of the river systems has been made difficult by several factors, which will be outlined in this paper.

The most relevant research on the evolution and hydrodynamics of the tidal rivers and coastal plains in the ARR will be reviewed. The strengths and weaknesses associated with this research will be discussed and future recommendations provided.

REGIONAL SETTING

Location of the Alligator Rivers Region

The Alligator Rivers Region is located in the wet-dry tropics of northern Australia, between latitudes 12^0S and 14^oS (Cobb *et al.*, 1997). The region flanks the south-eastern shore of van Diemen Gulf and includes the catchments of the four main estuarine river systems: the large South Alligator and East Alligator Rivers and the smaller West Alligator and Wildman Rivers, and encompasses the $20{,}000km^2$ Kakadu National Park (Figure 1) (Finlayson and Von Oertzen, 1996). The wider ARR encompasses the western estuarine river systems including Adelaide and Mary Rivers (Figure 2).

Climate

General Climate Description

Climate conditions have been described by a range of authors including Southern (1966), McAlpine (1969), Christian and Aldrick (1977), Chappell and Bardsley (1985), Taylor and Tulloch, (1985), Woodroffe *et al.* (1986), Wasson (1992), Butterworth (1995), Russell-Smith *et al.* (1995), McQuade *et al.* (1996) and Bureau of Meteorology (1999). Although the climatic records are limited, a general description of the climate of the ARR can be made on the basis of these authors' works.

The ARR is defined as lying within the wet-dry tropics as a result of the two distinct rainfall seasons: a wet season from November to March and a dry season from May to September (Southern, 1966; Chappell and Bardsley, 1985; Woodroffe *et al.*, 1986). The wet season is marked by monsoonal depression bringing heavy rain and occasional tropical cyclones, which produce torrential rain (Russell-Smith *et al.*, 1995). Hence, the rainfall regime is highly seasonal but reliable, as it does not appear to vary greatly in seasonality (Southern, 1966; McAlpine, 1976; Taylor and Tulloch, 1985). About 92% of the average rainfall falls between November and March (McQuade *et al.*, 1996). In contrast, little rain falls during the dry season months and its occurrence is more variable than the wet season rainfall (Wasson, 1992). Mean daily minimum and maximum temperatures for the ARR are 19.2^0C and 30^0C in July and 25.2^0C and 31.3^0C in November at the onset of the wet season (McAlpine, 1976). Between April and September, the winds are predominantly from the south-east and east and blow offshore, while from November to February the winds are more variable, often having a strong onshore westerly and northerly component (Bureau of Meteorology, 1999).

Available records

The climate record for the ARR is being investigated by Saynor *et al.* (2000) as part of a program for assessment and monitoring of coastal change within the region. Saynor *et al.* (2000) has found the climate coverage of the ARR it be intermittent, as it is concentrated around settled areas or those subject to mining development. Thus, the information can only provide an indication of the climate influencing the ARR and adjacent areas (Saynor *et al.*, 2000).

The climate coverage is not only very limited but the length of the records are relatively short (Saynor *et al.*, 2000). Shortest is from Jabiru which has a timespan of 18 years, while the longest climate record is from Gunbalunya (Oenpelli) which has a duration of approximately 80 years (Saynor *et al.*, 2000). Saynor *et al.* (2000) found rainfall data to be the most common climatic parameter collected but coverage is limited as stations are mostly associated with human settlements. More complete climate records, which include air and soil temperatures, wind speed and direction, pressure and humidity are restricted to mining sites located in the region (Saynor *et al.*, 2000).

The limited climate record is a major shortcoming for the interpretation for the processes present in the ARR as it hinders detailed analyses and modelling of the behaviour of the van Diemen Gulf oceanography, stream and estuarine hydrology and vegetation distributions (Saynor *et al.*, 2000). In turn, it is these studies that allow detailed process studies to be undertaken. This is probably one of the main reasons why such process studies are lacking in the ARR.

Geomorphology

The geomorphic investigations on the South Alligator River by Woodroffe *et al.* (1986) and small scale studies on the Lower Mary River Plains (Woodroffe and Mulrennan, 1993), East Alligator River (Wasson, 1992; Nanson, 1993), Adelaide River (Woodroffe *et al.*, 1993) have provided general descriptions on the present geomorphology. The most detailed geomorphic descriptions are based on the South Alligator River by Woodroffe *et al.* (1986).

Woodroffe *et al.* (1986) subdivided the plains and wetlands of the South Alligator River into three morphological provinces on the basis of landform, sediment patterns and the dominant processes in operation, which were mainly inferred. These were the coastal, deltaic-estuarine and alluvial plains provinces (see Figure 3) (Woodroffe *et al.*, 1986). A number of morphological units were recognised within each province which are summarised in Table 1 (Woodroffe *et al.*, 1986). Woodroffe *et al.* (1986) identified four channel types; the estuarine funnel, sinuous segment, cuspate segment and upstream tidal channel (see Figure 4).

The morphology of other estuarine river systems and associated plains in the ARR including the Mary, Adelaide and East Alligator Rivers have been described in a similar fashion adopted by Woodroffe *et al.* (1986). This allows for comparative analysis, despite being less detailed. Given the geomorphic variation of the estuarine river systems and associated plains of the ARR, detailed geomorphic descriptions are lacking to some extent. The estuarine river systems and plains are extremely large e.g. South Alligator River Basin is 11000km^2, which makes it difficult to characterise each system in detail and prohibitively expensive.

HYDRODYNAMICS OF TIDAL RIVERS AND COASTAL PLAINS

Hydrology

The hydrology of the river systems is highly seasonal, in response to the pronounced seasonality of the monsoonal rainfall regime upon the tidal-floodwater interface (East, 1996). Freshwater discharge into the tidal rivers is regulated by wet season monsoonal rainfall, where during the wet season the water in the estuarine reaches is predominantly fresh, becoming more saline in the Dry season when runoff from the catchment declines and eventually ceases (Woodroffe *et al.*, 1986; East, 1996). During the dry season, tidal forces dominate the estuarine reaches in which the spring tidal range in the van Diemen Gulf (5 to 6m) affects the river flow up to 105km inland (Woodroffe *et al.*, 1986, 1989).

Although a general description of the hydrology of the river systems is provided by Woodroffe *et al.* (1986) and East (1996), the hydrology of the ARR is incompletely defined. The lack of detailed hydrologic studies is due to a number of factors. For example, the large number of tributaries entering through the plains and wetlands such as on the South Alligator River, make gauging impractical (Woodroffe *et al.*, 1986). The hydrological data from the limited number of gauged stations deployed throughout the region is insufficient to estimate the volumes of total basin runoff (Vertessy, 1990). As a result, wet season flood discharge cannot be determined directly (Vertessy, 1990). In addition, the high interannual variability in the rainfall of the region and lack of data describing climatic variation, make it difficult to gain a detailed understanding of the hydrological processes operating in each river system (Walden, 2000).

Hydrological Models

As the hydrologic behaviour of most rivers in the ARR cannot be analysed in any detail due to the lack of gauges and thus hydrological data, the hydrology has been modelled. The Daly River outside the ARR, about 300km from the South Alligator River, has been adequately gauged to permit characterisation of the wet season flood frequency and magnitude (Chappell and Bardsley, 1985). The freshwater discharge behaviour of the Daly River summarised by Chappell and Bardsley (1985) has been used to estimate the wet season flood contribution for the rivers in the ARR. Although the Daly River is located outside the ARR, it is believed that it has sufficient in common with the estuarine river systems in this region (Chappell and Bardsley, 1985).

The freshwater discharge behaviour of the lower Daly River has been summarised by Chappell and Bardsley (1985) using a decade of records from ten gauging stations and three rainfall stations. According the Woodroffe *et al.* (1986) and Chappell and Woodroffe (1985) the rainfall-discharge relationship in the Daly River can be used to estimate the likely wet season hydrologic behaviour of the South Alligator and Adelaide Rivers. Woodroffe *et al.* (1986) estimated the freshwater discharge for the South Alligator River based on the wet season flood discharge records for the Daly

River which were scaled to account for differences in catchment size, geometry and rainfall amount. The average wet season discharge for the South Alligator River were estimated to be between 400-700 m^3s^{-1} (Woodroffe *et al.*, 1986). This scaling technique provides crude estimates but these are the best available estimates of wet season flood contribution to date.

A more detailed hydrological model has been based on a concentrated study of the Magela Creek and its floodplain, East Alligator River (see Figure 1) by Vardavas (1988; 1989). A daily rainfall-runoff model was developed to predict the fate of contaminants that may enter the surface waters of the Magela Creek and its floodplain from Ranger uranium mine. It is a simple water balance model using daily rainfall, averaged over the Magela catchment and monthly-averaged daily evaporation to predict the daily discharge at the catchment outlet (Vardavas, 1988). Although it can be considered a 'simple' model, it does take into account the complex water transfer processes and models the three main hydrological phases: (1) rapid wetting phase (2) slow infiltration phase and (3) slower evaporation phase. The model has been validated by examining its ability to predict measured daily water depth at the floodplain's outlet for twelve years, for which full data sets are available (Vardavas, 1989). Unfortunately, this simple statistical runoff model is not portable to other catchments and thus cannot be used to gain greater insight into the wet season hydrology of the large coastal basins discharging into the rivers of the ARR (Vardavas, 1989).

Tidal Hydrodynamics

Tidal hydrodynamics of the estuarine reaches of the tidal rivers in the ARR have been both measured directly in the field and indirectly through numerical modelling techniques. Several investigations on tidal hydrodynamics have been undertaken for various rivers in the region. The tidal behaviour of the South Alligator River has been investigated by Woodroffe *et al.* (1986), the Lower Mary River by Woodroffe and Mulrennan (1993) and the Adelaide River by Chappell and Woodroffe (1985). However, the most detailed study of tidal hydrodynamics for the South Alligator, Adelaide and Daly Rivers has been provided by Vertessy (1990). Woodroffe *et al.* (1986) and Chappell and Woodroffe (1985) provided the first concerted efforts in both measuring and modelling tidal hydrodynamics, however, Vertessys' (1990) study has significantly improved these earlier investigations.

Similarly to wet season hydrology, there are problems associated with characterising the tidal behaviour of these river systems. Firstly, the sheer size of the systems presents a major difficulty in characterising the variation in tidal behaviour both within and between each river system. The highly dynamic nature of the tides and associated currents in these rivers means that the time scales of change in the hydrodynamic processes are short. As mentioned in the previous section, there are problems in measuring wet season flood contributions, which poses difficulties in defining the interaction between tidal flows and wet season floods in the estuarine reaches of the tidal rivers. These problems were recognised by Vertessy (1990), and structured the methodology appropriately. For example, the use of tide gauges throughout the rivers enabled spatial and temporal variation in tide height to be resolved simply. The fundamental problem of inadequate spatial and temporal coverage of current velocity data, and the lack of wet season hydrodynamic data, was overcome by the application of numerical modelling techniques.

Field and Analytical Techniques

The main field techniques employed in Vertessy (1990) were similar to previous studies by Woodroffe *et al.* (1986), Chappell and Woodroffe (1985) and Woodroffe and Mulrennan (1993). Tide height measurements were obtained using portable tide gauges located at four stations along the river. Flow meters were used to measure current velocity through the vertical profile at each station and current meters were used to measure cross-sectional variations in current velocity. While the data collected during the field survey provided good first order approximations of tidal behaviour, there were no detailed observations made of tidal modification by wet season fluvial floods (Vertessy, 1990). Data was also patchy as the length of measurements varied from eight days to four weeks and tidal behaviour between widely spaced gauging stations was not accounted for (Vertessy, 1990). These problems were also encountered in the previous investigations.

The strength of this study lies in the development of a tidal model that allows accurate extrapolation beyond the observed data and provides good predictions of wet season flood contributions. The one-dimensional non-linear tidal model (CORAL) has significant advantages over the previous tidal model developed by Woodroffe *et al.* (1986). Woodroffe *et al.* (1986) used a one-dimensional linear tidal model to simulate tidal behaviour in the South Alligator River. The model gave reasonable first order estimates of tidal stage and discharge. However, it could not predict ebb-flood asymmetry of tidal stage, current or discharge, which constrained its use (Vertessy, 1990). Field observations indicated that tides become highly symmetrical with distance upstream in the South Alligator River (Woodroffe *et al.*, 1986), and therefore tidal asymmetry needs to be accounted for. For these reasons, Vertessy (1990) considers this linear tidal model to be inappropriate in modelling tidal behaviour.

The one-dimensional non-linear model developed by Vertessy (1990), adequately described the tidal behaviour as it was in good agreement with the observations of tidal stage, amplitude and asymmetries and current velocities. This model can accurately predict important hydrodynamic parameters such as the duration of the ebb-flood tidal hemicycle, which was a major shortcoming of model used by Woodroffe *et al.* (1986). Other parameters included ebb and flood discharge and current velocity (Vertessy, 1990). The ability to accurately predict these parameters overcomes the main problems in characterising tidal behaviour in large and highly dynamic river systems, previously mentioned.

Saltwater Intrusion on the Coastal Plains

Over the last 50 years, saltwater has intruded low-lying freshwater wetlands on the coastal plains through landward extension of tidal creeks (Cobb *et al.*, 2000). The process of tidal creek extension within the ARR has been well documented for the Lower Mary River Plains by Knighton *et al.* (1991, 1992) and Woodroffe and Mulrennan (1993) and the South, East and

West Alligator Rivers by Cobb (1997) and Cobb *et al.* (2000). However, the mechanism that has triggered this process has not been identified and there is much dispute, which is far from resolved.

Methods Used to Measure the Process of Saltwater Intrusion

Mapping the process of tidal creek extension from aerial photographs has been the principle method of examining the process of saltwater intrusion on coastal plains. Knighton *et al.* (1992) reconstructed the progress of network expansion of tidal creeks on the Lower Mary River Plains from detailed maps drawn from aerial photographs, taken between the years 1943-1991. Each tributary was assigned a number and a set of rules based on the difference between consecutive dates to determine the presence and absence of each stream. The problem of variation of scale and quality of aerial photographs was overcome by standardization to a common aerial photograph. The investigation revealed that the rapid expansion of the tidal network since 1943 was through headward extension and tributary development (Knighton, 1992).

This method was adopted by Cobb (1997) and Cobb *et al.* (2000) in determining the spatial extent and rate of saltwater intrusion for all rivers in the ARR. Prior to the research undertaken by Knighton *et al.* (1992) and Cobb (1997) the comparison between different regions was difficult due to variations in both scale and format. As saltwater intrusion is a major coastal management problem in the ARR, comparative analysis is essential in order to determine the geographic extent of the problem (Cobb *et al.*, 2000).

Hydrodynamics of Tidal Creek Extension

A preliminary investigation on the hydrodynamic processes involved in the development of tidal creek networks was undertaken for the Lower Mary River Plains by Woodroffe and Mulrennan (1993). In attempt to model the tidal behaviour of the rapidly extending Sampan Creek network, tidal gauges were employed along the main channel. Gauging was undertaken in the late dry season spring tide to reflect the influence of wet season floods and in the middle of the dry season representing tidal forces in the absence of fluvial input. Current velocity was measured and suspended sediment samples were collected at each gauging station.

Preliminary observations on tidal hydrodynamics confirm that tidal flows are actively evolving as the creek system expands. This supports the inference made by Knighton *et al.* (1992) who suggests increased tidal action results in rapid tidal creek extension. Preliminary calculations of tidal discharge indicate that tides become increasingly asymmetrical with distance upstream (Woodroffe and Mulrennan, 1993). Over one tidal cycle it was estimated that the flood tide carried about 7000 tonnes of sediment upstream at the mouth and the ebb carried about 5800 tonnes downstream (Woodroffe and Mulrennan, 1993). Woodroffe and Mulrennan (1993) emphasize that these are gross estimations, and cannot be used to extrapolate long-term budgets. However, these estimates demonstrate the potential of tidal asymmetry to generate upstream and downstream sediment movement (Woodroffe and Mulrennan, 1993).

Data acquired during this investigation was inadequate to gain a detailed understating of the hydrodynamics of the rapid evolving tidal creek network. In contrast to Vertessy (1990), data could not be used to calibrate a model for describing tidal behaviour in the tidal creek system. However, this preliminary investigation does provide a baseline for future monitoring and techniques in data acquisition required to calibrate hydrodynamic models. The tidal model developed by Vertessy (1990) may be applicable in this context.

Processes Responsible for Saltwater Intrusion

There is much dispute over the mechanisms responsible for saltwater intrusion into low-lying coastal plains. Also, there is much uncertainty in the evidence supporting different arguments. Woodroffe *et al.* (1986) argues that an increase in tidal amplitude as a result of late-Holocene meander cutoff is the dominant cause of tidal creek extension on the South Alligator River. However, Vertessy (1990) disputes this conclusion and calculates that tide heights in the modern river should in fact be lower.

The key in resolving this argument lies in examining the methods that were used to arrive at these separate conclusions. Woodroffe *et al.* (1986) used two sets of data to demonstrate their case: (1) survey data comparing the upper elevation of mangrove vegetation along the river with upper elevations of buried mangrove pollen assemblages and (2) comparison of tide height data for the modern river with tide height predictions for the assumed palaeo-river obtained using their one-dimensional linear tide model. Woodroffe *et al*. (1986) found an abrupt increase in the difference between upper elevations of modern and palaeo mangroves within the cuspate segment. Based on the assumption that mangroves are reliable indicators of high tide levels, Woodroffe et al. (1986) argues that this divergence reflects an increase in tidal amplitude in the upper reaches of the estuarine river. This was associated with late-Holocene meander cutoff and cuspate meander formation. By contrast, Grindrod (1988) cautions against this interpretation noting that sediment compaction results in the downward movement of mid-Holocene mangrove deposits.

The one-dimensional linear tide model was used to predict tide heights for the palaeo-river using the sinuous Adelaide River as an analogue. Tidal parameters of the modern South Alligator River were compared against parameters calculated and inferred for the assumed palaeo-river. From this it was concluded that the full set of effects of changes in channel form: change in friction, shallowing and change from sinuous to cuspate, amounts to a 1.1m increase in spring high water level since late-Holocene (Woodroffe *et al.*, 1986).

As previously mentioned, Vertessy (1990) considers the one-dimensional linear tide model developed by Woodroffe *et al.* (1986) inappropriate to model tidal behaviour. Tidal simulations performed using the one-dimensional non-linear tidal model, were used to compare tidal behaviours of the modern and assumed palaeo-forms of the South Alligator River. The maximum tide levels and tidal ranges were predicted to be lower for the modern river, which conflicts with Woodroffe *et al.* (1986). Vertessy (1990) states that meander cutoff and cuspate formation during the late-Holocene has acted to decrease tidal ranges in this segment.

The argument proposed by Vertessy (1990) appears to be more feasible than that by Woodroffe *et al.* (1986) based on the examination of the different methodologies used. However, Vertessy (1990) has not offered another reason why spring high tide levels in the modern river are higher. This dispute has not been resolved to any extent. However, this improved understanding of tidal river hydrodynamics based on the study by Vertessy (1990) may help to resolve future questions regarding future changes to tidal rivers systems in the ARR.

EVOLUTION OF ESTUARIES AND COASTAL PLAINS

Most of the research to date, has been focused on the Holocene development of the estuarine reaches and coastal plains in the ARR. The development of this region occurred in response to Post Glacial Marine Transgression and subsequent stabilisation of sea level to its present level (Woodroffe *et al.*, 1986). Consequently, there has been limited research directed at examining more recent changes, such as over the last 1000 years. The most detailed studies on the Holocene evolution are on the South Alligator River by Woodroffe *et al.* (1985, 1986, 1989, 1993) and Chappell (1985). Other studies have been focused on smaller scales, such as on the Magela Plain (Clark and Guppy, 1988; Wasson, 1992; Nanson *et al.*, 1993), coastal plains and estuarine reaches on the Adelaide River (Woodroffe *et al.*, 1993) and the Lower Mary River Plains (Woodroffe *et al.*, 1993; Woodroffe and Mulrennan, 1993).

Stratigraphy, Palynology and Radiocarbon Dating

Stratigraphic drilling, palynology and radiocarbon dating have been the main techniques used to reconstruct the Holocene evolution of the South Alligator River and other rivers in the ARR. Stratigraphic drilling has allowed identification of stratigraphic units, which provides information about the sediments that infilled the tidal river valleys during the Holocene. Stratigraphic units have been distinguished on the basis of texture, grain size, organic content and the presence of sedimentary structures such as foraminifera and mangrove fragments. This has provided insight into the type of sedimentary environment e.g. freshwater, estuarine or marine. (Woodroffe *et al.*, 1986)

Radiocarbon dating of organic material preserved within the stratigraphic units has been used to determine the time of deposition (Woodroffe *et al.*, 1986). Although the half-life of radiocarbon (5730 years), ^{14}C, is applicable to the Holocene period (last 10,000 years), there are problems associated with this technique. The main problem being that the time of death does not always equal the time of deposition (Wasson, 1992). Organic material deposited *in situ* such as mangrove stumps, are the best material to radiocarbon date (Woodroffe *et al.*, 1986). Radiocarbon dating of organic fragments induce error into the interpretation of the stratigraphic record. The ‘Big Swamp’ model developed by Woodroffe *et al.* (1986) was based mainly on radiocarbon dates on mangrove fragments, which presents many uncertainties.

Pollen analysis provides more detailed information about the palaeoenvironments (Chappell and Grindrod, 1985). Analysis of sediments alone cannot provide detailed information on transition periods, such as the transition from mangrove estuarine environments to freshwater environments, such as on the Magela Plain, 2000 years ago (Clark and Guppy, 1988). Pollen analysis has been viewed as a powerful tool that allows insight into vegetation communities that existed during the Holocene (Chappell and Grindrod, 1985; Clark and Guppy, 1988). However, pollen can only be identified to taxa level, which is not always valid interpretation of past environments. Some freshwater grass species can tolerate more saline environments than estuarine species and *Barringtonia acutangula* is a freshwater mangrove (Clark and Guppy, 1988). Future employment of Scanning Electron Microscope (SEM) would allow identification to species level in contrast to the presently employed light microscope.

Conceptual Models

The widely accepted model of Holocene development of tidal rivers in the ARR is comprised of estuarine infill and coastal progradation (Woodroffe *et al.*, 1986, 1989, 1993). The South Alligator River has been investigated in the most detail in which three phases of development were identified through stratigraphic analysis, palynology and radiocarbon dating (Woodroffe *et al.*, 1986). Three phases of estuarine infill recognised were: (1) a transgressive phase (8000-6800 years B.P.) of marine incursion; (2) a big swamp phase (6800-5300 years B.P.) of widespread mangrove forest development; and (3) a sinuous/cuspate phase of floodplain development since 5300 years B.P. (Woodroffe *et al.*, 1986). It is believed that since 6000 years B.P., the South Alligator coastal plain has prograded with two phases of chenier ridge formation, which has also been recognised on the Adelaide and Mary Rivers (Woodroffe *et al.*, 1986,1993; Woodroffe and Mulrennan, 1993).

There is evidence to support the Holocene model of estuarine infill and coastal progradation, first proposed by Woodroffe *et al.* (1986). The model has been generally accepted but it does embody some uncertainties. These will be discussed for each proposed phase of development.

Transgressive Phase, 8000-6800 years B.P.

The transgressive phase of estuarine development was first identified on the South Alligator River by Woodroffe *et al.* (1986). The presence of mangrove mud overlying the valley surface bottom is believed to represent tidal flooding of the South Alligator River valley in response to sea level rise (Woodroffe *et al.*, 1986). Radiocarbon dating of this unit, performed mostly on mangrove fragments indicate this unit was deposited between 8000-7800 years B.P. Woodroffe *et al.* (1986) refers to this mangrove mud unit as ‘transgressive’, as the time of deposition coincides with sea level rise evident in sea level data from eastern Australia. However, Woodroffe *et al.* (1986) acknowledge that sea-level data may not exactly apply to the South Alligator River, nor other rivers in the ARR.

To resolve this problem, Woodroffe *et al.* (1986, 1987) constructed a Holocene sea level curve for the south-eastern van Diemen Gulf. The sea level curve is an age-depth plot of radiocarbon dates on mangrove fragments. Woodroffe *et al.* (1986) consider mangroves to be good indicators of sea level because they are almost exclusively found growing intertidally. This is a feasible assumption as present day analogies exist throughout the ARR, where mangroves are found fringing the coastline of the van Diemen Gulf.

Woodroffe *et al.* (1986, 1987) have demonstrated good agreement in terms of age and depth between basal samples. This indicates that the problem of sediment compaction and downward displacement of material noted by Chappell and Grindrod (1984) does not apply. Although, the sea level curve barely over laps that from eastern Australia, the course of sea level rise is clearly apparent (Figure 5).

Evidence to support this transgressive phase has been found on other rivers in the ARR. The 'transgressive' mangrove mud unit has been identified on the Adelaide River by Woodroffe *et al.* (1993) and confirmed through pollen analysis by Grindrod (1988). Similarly, Woodroffe and Mulrennan (1993) note the presence of this unit throughout the Lower Mary River Plains. Radiocarbon dates from all areas investigated are synchronous with sea level rise.

Big Swamp Phase, 6800-5300 years B.P.

Stratigraphic sections based on drillholes, indicate thick accumulation of mangrove mud along estuarine reaches, first noted on the South Alligator River by Woodroffe *et al.* (1986). The widespread occurrence of the upper mangrove unit, radiocarbon-dated 6800-5300 years B.P., indicates that a 'big swamp' of extensive mangrove forest existed throughout the estuarine reaches of the tidal rivers (Woodroffe *et al.*, 1987). Pollen analysis indicates that the mangrove forest was, predominantly *Rhizophera* species. Similar evidence of this phase has been found on the Adelaide River by Grindrod (1988) and Woodroffe *et al.* (1993), Magela floodplain on the East Alligator River by Clark and Guppy (1988) and Lower Mary River by Woodroffe and Mulrennan (1993).

The 'Big Swamp' model has been widely accepted and is preferred over the general progressive progradation model for various reasons. Woodroffe *et al.* (1986) concludes that the apparent lack of spatial trends between radiocarbon dates on mangrove fragments along the length of the river supports 'Big Swamp' model. The progradation model implies mangrove sediment should become progressively younger in the seaward direction (Woodroffe *et al.*, 1986). No evidence of this trend has been found on any river investigated in the ARR.

One source of error in these investigations is the dating of fine mangrove fragments. For all investigations, mangrove fragments were the main material dated in the mangrove mud unit. Mangrove fragments could have been redistributed numerous times before deposition, thus providing unreliable radiocarbon dates. However, the reliability of radiocarbon dates have not been questioned. Woodroffe *et al.* (1985) infer that 'Big Swamp' sedimentation occurred in other macrotidal estuaries, such as the Ord and Fitzroy in north Western Australia, offering further support for this model, however radiocarbon evidence is only minor. No evidence has been found to suggest the 'Big Swamp' model to be inappropriate.

Sinuous/Cuspate Phase since 5300 years B.P.

Radiocarbon dating of channel infill, laminated channel sediments, palaeomenader bends and connection of visible palaeochannels have proven to effective techniques in reconstructing past channel changes (e.g.

Woodroffe *et al.*, 1986, 1993; Chappell, 1988; Woodroffe and Mulrennan, 1993). Based on these techniques, Woodroffe *et al.* (1986) have demonstrated that the South Alligator River was in its former sinuous course by 4000 years B.P. (Figure 6). This former sinuous segment is now a series of cuspate meanders, which are wider, shallower and less sinuous (Woodroffe *et al.*, 1986). The exact time of abandonment of sinuous meanders is unknown although radiocarbon dates on channel infill indicate cuspate meanders were present around 2000 years B.P. (Woodroffe *et al.*, 1986). Also, it has not been determined whether transition from sinuous to cuspate was continuous or episodic (Woodroffe *et al.*, 1986). However, from radiocarbon dates of palaeochannels, Woodroffe *et al.* (1986) infer that cuspate meanders formed at the expense of sinuous bends.

During this time period, Woodroffe *et al.* (1993) and Woodroffe and Mulrennan (1993) have demonstrated that the Lower Mary and Adelaide Rivers have actually switched channel courses, in contrast to the South Alligator River. It is unclear how this occurred but it has been hypothesized that seaward sediment source has contributed to channel diversion on both rivers as opposed to a fluvial source (Woodroffe *et al.*, 1986, 1993). This hypothesis has been based on several factors. The presence of foraminifera preserved in laminated palaeochannels indicate that part of the sediment deposited during this time is marine (Woodroffe *et al.*, 1993). Also, if it were just a matter of fluvial reworking since the Big Swamp phase, or a lack of channel maintenance, then both rivers would have been blocked in a similar fashion. The Adelaide and Mary Rivers have similar catchment flows but the Adelaide has undergone divergence while the Mary River has been completely blocked (Woodroffe et al, 1993).

Coastal Plain Development Since 6000 years B.P.

Woodroffe *et al.* (1986) refer to coastal progradation as episodic. This has been in response to different stages of estuarine development since the end of the ‘Big Swamp’ phase, about 4000 years ago. Woodroffe *et al.* (1986) indicate that evidence supporting this episodic nature of coastal plain development is contained in the coastal plain stratigraphy. Radiocarbon dates of shell detritus and shell fragments from the marine fine sands indicate rapid progradation between 4000 and 3000 years B.P. (Woodroffe *et al.*, 1986). These dates coincide with the end of the ‘Big Swamp’ phase and development of the sinuous channel, which suggests that the coastal plain on the South Alligator developed as a result of an increased availability of mud. Similar evidence on the Lower Mary Plains has been provided by Woodroffe and Mulrennan (1993).

Caution must be taken when interpreting this evidence. Although the dates coincide with the end of the ‘Big Swamp’ phase, they have been mainly based on fine shell fragments. Intertidal zones along coastal plains are highly active environments, which implies intense reworking of sediment and material. Whole shells allow taxa or species identification which inturn allows habitat interpretation. These shell fragments may not have been of estuarine origin, thereby offering no support to the interpretation offered by Woodroffe *et al.* (1986).

CONTEMPORARY RESEARCH

Investigations into more recent changes that have occurred in the ARR are lacking. Consequently, the contemporary processes responsible for change are unknown. For example, the process of saltwater intrusion on low-lying coastal plains through tidal creek extension is well understood, however no casual effect has been identified (Cobb *et al.*, 2000). Woodroffe and Mulrennan (1993) provide evidence of shoreline change on the Lower Mary River, which has changed rapidly in both nature and position. However, the contemporary processes responsible and its link to saltwater intrusion have not been identified to any significant extent.

The Holocene development of estuarine reaches and coastal plains has been the main focus of the research in the ARR. The only research that has provided information on changes during the last 2000 years has been associated with the Ranger uranium mine. Wasson (1992) reconstructed the sedimentation rates and depositional pattern of the freshwater clays on Magela floodplain. This investigation was used to provide insight into the fate of uranium tailings, which are expected to erode from the tailings dam near the Ranger uranium mine within the next 200 years (Wasson, 1992). This study is only applicable to the Magela Creek catchment and thus is not portable between other floodplain environments in the ARR.

CONCLUSIONS

The main strengths and weaknesses of the geomorphological research pertaining to the hydrodynamics and evolution of the tidal rivers and coastal plains are summarised in Table 2. More detailed interpretations of individual studies are provided in Appendix 1 and 2.

The research regarding the hydrodynamics of the tidal rivers and coastal plains has been made difficult by the lack of data on wet season hydrology. To date the Daly River provides the best hydrologic record, however it is located outside the ARR and the scaling techniques provided by Woodroffe *et al.* (1986) give crude estimates. However, hydrodynamic research in the ARR has been strengthened by the study undertaken by Vertessy (1990). The one-dimensional non-linear tidal model has provided an improved understanding of tidal hydrodynamics in the estuarine reaches and accurate estimates of wet season flood contributions.

Regarding saltwater intrusion, the model developed by Vertessy (1990) has the potential to provide a greater understanding on the hydrodynamic processes in tidal creek networks. However, this has not been recognized in the literature. Tidal modelling developed by Vertessy (1990) coupled with sediment transport modelling should be examined further to help discern which floodplain systems will be subject to high-risk flooding and saltwater intrusion in the future.

The Holocene development of estuarine reaches and coastal plains has been investigated in detail, which has been a major strength of the research undertaken in the ARR. This research increases the capacity to predict future changes that are likely to take place, given a future rise in sea level. However, the hypothesized seaward sediment source proposed by Woodroffe *et al.* (1986) needs to be tested. Coring in the van Diemen Gulf would provide this information and would provide a more complete picture of changes that occurred during the Holocene.

A major shortcoming of the research undertaken in the ARR, is the lack of contemporary studies on process and change. The geomorphology of the ARR has been described in some detail, but given the geomorphic variation within and between the tidal river systems, this is largely unknown. Cobb (1997) came close to providing a process-based study through documentation of geomorphic changes on the coastal and estuarine plains associated with saltwater intrusion. However, processes responsible for changes could only be inferred. The experimental design for future investigations on contemporary geomorphic change should be process-based and directed at finding evidence of processes responsible. However, before process-based studies can be undertaken, more detailed investigations on the present geomorphology of the region are required.

Table 2. Summary of the main strengths, weaknesses and future recommendations regarding research in the ARR

Strengths	Weaknesses	Future Recommendations
An improved understanding of tidal hydrodynamics in the estuarine reaches has been provided by tidal model developed by Vertessy (1990)	Limited climatic records	Establish additional weather stations in which their location should be strategically chosen to integrate with system modelling and climate analysis
Detailed understanding of the process of tidal creek extension.	Lack of stream gauging stations in the ARR and thus lack of hydrological data to model wet season hydrology	Improve hydrological monitoring in the ARR by improving stream gauge network.
Geographic extent of saltwater intrusion within the ARR has been identified by Cobb (1997). This study has provided a baseline for future monitoring.	Unresolved conflicts regarding the mechanisms responsible for an increase in spring high tide levels in the tidal river systems	Locations that have poor coverage must be identified and the location, type and scale of hydrological modelling must be defined to limit costs.
Stratigraphic analysis of estuarine reaches on tidal rivers and coastal plains has provided a general picture of their development during the Holocene	Lack of investigations on more recent changes that have occurred during the last 100 years. This is a major shortcoming of research undertaken in the ARR and has prevented the identification of processes responsible for change. For example, the process(s) responsible for saltwater intrusion.	Development of more sophisticated flood runoff models to improve estimates of wet season flood contributions
Stratigraphic analysis, supported by radiocarbon dating and substantiated by pollen analysis, has allowed identification of three broad phases of estuarine infill and coastal plain development		Tidal modelling developed by Vertessy (1990) coupled with sediment transport modelling should be examined further to help discern which floodplain systems will be subject to high risk flooding and saltwater intrusion in the future
		Preliminary studies on hydrodynamic processes in tidal creek networks by Woodroffe and Mulrennan (1993) should be used as a baseline for future monitoring and development of hydrodynamic models
		Investigation into both present day and past dynamics of the van Diemen Gulf is required to test the hypothesis of an seaward sediment source during the late-Holocene. Coring in the gulf would provide this evidence
		Detailed investigations on contemporary changes in the ARR are required for identification of processes responsible for change

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1,27,28,36,40,41,46,47,54,56,61,65,69,71,72,74,75,77,78,81,82,87,91,92,93,94,95

Colour A3:
51,55,59,63

B/W A3:
48

Please note that Appendix B is not in pdf format due to problems with conversion. It must be printed as a word document and then inserted into the final print out.