GEOMORPHOLOGY OF THE LOWER MARY RIVER PLAINS
NORTHERN TERRITORY

C.D. WOODROFFE AND M.E. MULRENNAN

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SUMMARY

- The extent and morphology of the Lower Mary River plains have changed markedly during the Holocene. Drilling, radiocarbon dating and pollen analysis indicate a transgressive phase that began about 7000 years ago as the rising seas flooded a prior valley, 6–9 m below present sea level. This was followed by a big swamp phase as sea level stabilised around 6000 years ago, during which widespread mangrove forests occurred south of Shady Camp. Gradual buildout of the coast took place at a decelerating rate since then from Alligator Head to a shoreline close to the present around 2000 years ago.

- Extensive mangrove wetlands have dominated the paleoestuarine plains throughout most of the Holocene. Freshwater wetlands have generally replaced these mangrove forests, and are geologically very young, having first appeared about 4000 years ago, and becoming extensive perhaps as recently as 2000 years ago. The freshwater wetlands, developed as a result of vertical sediment accumulation and shoreline progradation, are highly valued for their bird and fish populations, as well as for their native grasses.

- Paleochannels on the coastal plain indicate former, large estuarine channels, initially in the location of modern Tommecut Creek, then switching to a course to the west, and switching once more to an eastern course. Infill of these estuarine paleochannels appears to have been from marine or estuarine sediments, confining flow to fluvial channels prior to switching. Since about 2000 years BP the easternmost sequence of channels has filled in and more recent chenier ridges indicate that no single channel discharged directly into the Gulf during this period.

- Most of the plains are underlain by muds deposited in saline estuarine environments; there are large accumulations of salts within the plains and the high levels of pyrite in these sediments mean that these are potential acid sulphate soils. Salt could easily be remobilised, and highly acidic waters, with toxic levels of aluminium, could be released if these muds are exposed or water tables are allowed to drop a metre or more lower than usual.

- The topography of the plains, revealed by detailed surveying, indicates that large areas of the plains are below the level reached by the highest tides at the coast. Tidal creeks are preferentially reoccupying paleochannels which are flanked by levées, and represent corridors of high ground through the low-lying plains. Where levées are breached, in some cases by buffalo swim channels, the creek system expands rapidly across the low-lying coastal plains.

- There is no evidence to suggest that rapid tidal creek expansion has occurred previously during the Holocene in quite the manner that it has over the last 50 years. Although channel avulsion took place in the past, and though there is some evidence for reoccupation of the Tommecut paleochannels, there is no evidence of
previous widespread dendritic creek networks. The present phase of expansion does not appear to be a part of a regular cycle of paleochannel reoccupation.

- It is not possible to identify a single cause for the onset of tidal creek expansion in the 1930s or 1940s. Much of the plain was vulnerable because its elevation is below that of the highest tide, perhaps as a result of gradual consolidation and compaction since deposition during the mid-Holocene. Creek expansion over the last 50 years has also been demonstrated on other tidal systems in the region, and does not support a local cause, such as an extreme storm event, or unusual rainfall and runoff conditions. Buffalo have had a series of adverse impacts on the landscape, and associated swim channels have been exploited in some cases by individual creeks. High buffalo numbers appear to have coincided with the initiation of creek extension. Their activity may have triggered change through the breakdown of coastal ridges and levées, and hastened the pattern of network extension.

- Sea level rise does not seem to have been a cause of saltwater intrusion. There is no clear evidence for any change of mean sea level over the last 6000 years and evidence from elsewhere suggests that it has probably fallen slightly over that time. Analysis of tidal records shows no firm support for the suggestion that it is presently rising in the Top End. If sea level rises in the future, as predicted as a result of global warming, then the saltwater intrusion problem may be exacerbated, although the exact local impact will depend on the hydrodynamic response of creeks. In that event, the pattern of tidal creek expansion observed on the Mary plains might be seen more widely across the low-lying coastal plains of the Top End.

- The processes of creek network extension, elaboration, widening and reoccupation of paleochannels are now internally driven, and are likely to continue until an equilibrium state is reached. This may not be until the surface of the lower coastal plain accessible to creeks is occupied at a drainage density of around 10 km/km². Tidal discharge will increase as the system expands and the main creeks are likely to widen until they are similar to the fluvially-dominated paleochannels.

- The plains are not stable, but are part of a dynamic and at times rapidly changing system. Management and physical intervention needs to recognise and accommodate this changeability. Tidal wetlands, especially mangroves, though less productive than freshwater wetlands, represent ecologically significant resources, and may act to encapsulate tidal flows. Physical intervention may be necessary where landuse changes are unacceptable, or to prevent the loss of highly valued resources, but should be undertaken within the context of a wetland management strategy and predefined conservation priorities.
Figure 1 Major rivers draining into van Diemen Gulf; their catchments and the extent of coastal and estuarine plains
1. INTRODUCTION

The Mary River is one of several large seasonal rivers which drain northwards into van Diemen Gulf in the Northern Territory (Figure 1). It has a catchment area of about 7700 km$^2$. Most of its drainage is across a dissected, lateritised land surface, termed the Koolpinyah land surface, but near the coast it flows through extensive horizontal plains, covering about 1100 km$^2$ (see Table 1), which are the subject of this study.

The Mary River, unlike its neighbours, has not always reached the coast as a discrete channel. Instead it appears that up until the 1940s the river divided into a disconnected series of multiple channels or billabongs and that much of the peak Wet season floodwater overtopped the river banks, flooded the plains and evaporated from the plains surface. Since the 1940s this situation has changed as a result of saltwater incursion into low-lying areas and rapid headward extension of Sampan and Tommymcut Creeks. Sampan Creek is the present system's major outlet to the sea and extends as far south as Shady Camp, a natural rock bar, where a barrage presently prevents saltwater extending further up the freshwater Mary River system (Plate 1).

Plate 1 Shady Camp Barrage, at the landward limit of tidal influence, with the freshwater Shady Camp Billabong in the foreground
The plains of the Lower Mary River consist of a number of Conservation Reserves and several pastoral properties. The area contains some of the most productive pasture in the Northern Territory, supporting both cattle and buffalo on native grasses, such as *Hymenachne acutigluma* which is a valuable resource in the dry season, and the introduced Para grass, *Brachiaria mutica* (Applegate 1990).

In addition to pastoralism, the plains are of considerable aesthetic, conservation and recreational value. The wetlands are teeming with wildlife, most notably large breeding populations of magpie geese (*Anseranus semipalmata*), egrets, and other water birds. There are several barramundi fishing spots which are extremely popular with amateur anglers. Bordering Kakadu National Park, this area also offers considerable tourist potential with such opportunities as bird watching, photography, camping, pleasure boating, sightseeing and crocodile spotting (Sterling 1992). Several tourist developments have begun, and others are at the planning stage.

The plains represent one of the Northern Territory Government's most promising attempts at multiple land use, encouraging use of resources in a sustainable way. This approach is also targeted towards achieving Integrated Catchment Management. Local landholders formed the Lower Mary River Landcare Group in 1989 and, with the assistance of government agencies, are developing Property Management Plans embodying the concept of sustainable development (Nurse 1989).

Three major problems can be identified on the plains of the Lower Mary River. First, the plains are being affected by saltwater intrusion. Second, they are threatened by woody weed infestation, primarily by *Mimosa pigra*, and third they have been degraded by feral animals, notably buffalo until their eradication or domestication under the BTEC program, and more recently feral pigs (Sterling 1992).

This study addresses the issue of saltwater intrusion. In the 1940s the Mary River drained as a discontinuous series of linear billabongs and for most of the year did not reach the coast as a discrete channel. Since that time the two major tidal creeks, Tommycut and Sampan Creeks, have expanded, accommodating larger tidal flows, and extended as far south as the freshwater Shady Camp Billabong. The penetration of saltwater into the plains has stressed the natural vegetation, and led to extensive dieback of paperbark (*Melaleuca* spp.), grasses and sedges across these plains (Plate 2). In 1987 the Conservation Commission of the Northern Territory (CCNT) began restoration work. The Barrage was constructed in 1988 on top of a natural rock bar that partially divided the billabong at Shady Camp. Following some modifications in design in 1989, this structure has since served to limit the penetration of saltwater upstream into the freshwater system. A large block has also been established across a major paleochannel to the north west of the plains (Plate 3). Several minor earthen blocks have been placed across narrow tidal gutters to prevent further saline inundation at other sites, including locations where chenier ridges have been breached. These blocks also serve to slightly retard the drainage of freshwater from the plains.
Plate 2 Saltwater intrusion, resulting in extensive dieback of paperbark (Melaleuca spp.) on the coastal plains.

Plate 3 An earthen embankment preventing saline intrusion into the large paleochannel system on the western side of the coastal plain.
1.1. Regional Setting

1.1.1. Climate

The region between Darwin and the Alligator Rivers has a monsoonal climate with an annual average rainfall of between 1300 and 1600 mm, and with most rainfall during the Wet season, November to April (annual average precipitation at Opium Creek over a short period of observations was 1573 mm [Whitehead et al 1990]). The winds are dominated by easterlies during the Dry season, with less strong east to north winds during the Wet season (McAlpine 1969). Mean daily minimum and maximum temperatures are 19.2°C and 30.3°C in July and 25.2°C and 33.1°C in November. The annual cycles of rainfall, temperature and evaporation are important in determining the water balance; these are summarised (as calculated by McAlpine [1976] for Oenpelli) in Figure 2.

1.1.2. Hydrology

The flow of the Mary River is highly seasonal reflecting the monsoonal rainfall pattern. The river has been gauged since 1957 at the Arnhem Highway crossing near Mount Bundey (GS 8180035). Flood recurrence, determined using a Log-Pearson type III partial series analysis (Figure 4), suggests that: a flood of 500 cumecs recurs roughly annually; a flood of 2500 cumecs recurs on average once in 10 years; and a flood of 4500 cumecs recurs once in 100 years. Flood stage increases at the onset of the Wet season, exceeding 8 m (1900 cumecs) in the wettest years (stage reached 8.87 m—3100 cumecs—in March 1977). The flood peak rises with minor reversions (typically with an amplitude of about 1 m, two or three times a month), reaching a maximum around April, after which there is a gradual recession. The time of the peak can vary over several months, and in 1964–5 there were two flood peaks.

Other water-level records for the Lower Mary River are available from Roonnees Lagoon (GS 8180070) between 1957 and 1964, and from Shady Camp (GS 8180058) which began in 1957, and has been operational between 1957–1967 and 1975–1986, and returned to operation in September 1989 (Figure 3). Water-level records indicate that there was no regular tidal influence (defined as a tidally-induced variation in water level) at the Roonnees Lagoon station up to the gauge's closure in 1964 (though highest high tides can be detected from records in 1963 [Williams, pers. comm., 1992], and there was no tidal influence at Shady Camp as recently as 1986. A water quality survey conducted in August 1980 also confirms that the water was not saline in Shady Camp Billabong (Water Resources Division 1985). Salt stress was first observed there in 1987 (Applegate 1990).

The Lower Mary River plains are inundated primarily from overbank flow. Water level observations for the late 1950s and early 1960s suggested that there was a greater than 75% probability that the plains near the coast would be inundated in any year by the highest water levels in March-April (Purich 1966). This area of inundation will have increased considerably in recent decades. Direct precipitation and runoff contributes to water levels in backwater swamps.
Figure 2  a: Mean monthly rainfall at Oenpelli (P); b: Mean monthly water balance, P–E (evaporation, Fitzpatrick method (see McAlpine 1976) at Oenpelli; c: Mean monthly soil moisture storage at Oenpelli (McAlpine 1976), and cumulative P–E curve
Figure 3: Morphological provinces of the Lower Mary River, and locations referred to in the text.
At the peak of the Wet season, some freshwater drains from the plains, via elongate billabongs, into tidal creeks at the coast; however, much remains on the plains. Gradients which slope away from channels impair rapid drainage from depressions on the plains, and these areas dry slowly as a result of evaporation (Kingston 1991). Much of the plains dry to desiccation during the Dry season, and their surface black cracking clays break into polygonal cracks, often more than 50 cm deep (Plate 4).

Tommycut and Sampan Creeks are tidal. The tidal range at the mouth is around 5 m at springs, and high tide is delayed with respect to the tide predictions for Darwin. There is a further delay with distance upstream along the creeks, as tidal asymmetry increases (see Figure 9).
Plate 4 *Melaleuca* dieback area adjacent to a creek bed, with desiccation of black cracking clays into polygonal cracks in the foreground

1.1.3. Geology

The low-lying plains of the lower Mary River are Quaternary in age (Figure 5). All those that are the subject of this report are Holocene (ie, formed in the last 10,000 years), but Pleistocene and Holocene alluvium is widespread in the catchment (Stuart-Smith *et al* 1984). Much of the Mary River catchment is composed of lateritic plains (termed northern plains by Stuart-Smith *et al* 1984), developed over flat-lying Cretaceous and upper Tertiary sediments and peneplaned early Proterozoic sedimentary rocks (Williams 1976, 1991).

On the Arnhem Highway, around Mount Bundey and Mount Goyder, rugged tor-like outcrops of boulder-strewn granite, and resistant strike ridges of Early Proterozoic metasediments form dissected foothills up to 200 m above the plains (Pietsch & Stuart-Smith 1987). The early Proterozoic strike ridges trend NNE–SSW and outcrop through the Holocene plains, particularly on the eastern margin of the Mary River (ie, Flood Mark and Fire Dreaming Islands).
Figure 5 Geology of the Lower Mary River (based upon Pietsch & Stuart-Smith 1987)
1.1.4. Vegetation

Vegetation has been mapped at a broad scale during CSIRO studies of land systems within the region (Story 1969, 1976). The distribution of the main vegetation communities is summarised in Figure 6. The tall open forest of the lateritic plains is dominated by Eucalyptus miniat a and Eucalyptus tetrodonta with understorey trees such as Erythrophleum chlorostachys (Burgman & Thompson 1982; Wilson & Bowman 1987). Around the margins of the plains Eucalyptus papuana forms woodlands, generally with a grassy understorey (Pseudoraphis spinescens) and often with Eucalyptus alba, Pandanus sp. and Livistona benthamii. These margins present an elevational gradient with variations in flooding being the prime control on tree-species dominance (Bowman & McDonough 1991). Phyla nodiflora is also a common ground cover in this marginal habitat on the Mary River plains (Whitehead et al 1990).

The alluvial plains to the south of the study area contain mixed woodland and open woodland of Eucalyptus polycarpa, E. papuana, Acacia holosericea, A. auriculiformis and Barringtonia acutangula, and merge into stunted woodland of Melaleuca cajuputi and M. nervosa at the margin with the paleoestuarine plain. Channels on this sandy alluvium are fringed with Melaleuca argentea and M. leucadendra.

The vegetation of the Mary River plains has been studied by Whitehead et al. (1990). The most widespread wetland vegetation types are grass-sedgeland dominated by Pseudoraphis spinescens, either with Oryza rufipogon or Alternanthera nodiflora; sedgeland dominated by Eleocharis dulcis or E. brassii in deeper water (in both cases generally with Oryza and in depressions with Ipomoea aquatica); and extensive grassland of Hymenachne acutigluma (with Oryza and Polygonum attenuatum). Water depth, itself varying substantially throughout the year, appears to be the prime control on vegetation patterning on the Mary River plains (Whitehead et al 1990). Similar results have been found on the plains of the Adelaide River (Bowman & Wilson 1986), the South Alligator (Taylor & Dunlop 1985), and Magela Creek (Williams 1979). Small billabong depressions remain wet through most of the year and are dominated by Eleocharis spp. Larger billabongs with greater water flow are generally fringed with Pandanus spiralis, Barringtonia acutangula and locally Bambusa arnhemica. Paperbark dominates many of the low-lying backswamp areas, and the lower parts of the coastal plain (Melaleuca spp.). A schematic profile is shown in Figure 7.

A sequence of salt tolerant plants occurs at the coast, shown schematically in Figure 8. The coast consists of an extensive subtidal shelly and sandy mudflat; the lower intertidal is bare of vegetation, but there is, at least around Sampan Creek, a zone of dead mangrove stumps seaward of the living mangroves. The mangrove zone is of variable width and in some places appears to be eroding and elsewhere prograding (Woodroffe et al 1990). It typically consists of a seaward zone of Sonneratia alba and Avicennia marina, a central zone of mixed mangroves dominated by Rhizophora stylosa, and a landward zone of Ceriops tagal and Avicennia marina.
Figure 6  Vegetation communities of the Lower Mary River (based upon Story 1969, 1976, and Whitehead et al 1990)
Along much of the coast the next zone is one of succulent herbs, mainly *Sarcocornia*, *Halosarcia* and the salt-tolerant grasses *Sporobolus virginicus* and *Paspalum distichum*. Occasionally, as shown in Figure 8, there is a poorly-vegetated, infrequently mobile, sandy chenier ridge. Both the ridge and the saline mudflat contain stumps and dead individuals of mangroves, generally *Avicennia* (Plate 5).

1 Tall open forest, *Eucalyptus miniata, E.tetrodonta*
2 Plains margin, *Pandanus, Livistona, E.alba, E.papuana*
3 Sedgeland, *Eleocharis*
4 Paperbark, *Melaleuca*
5 Mixed grassland, *Oryza*
6 Sedge-dominated depression, *Eleocharis, Ipomoea*
7 Levee, *Pseudoraphis, Phyla*
8 Billabong fringe, *Pandanus, Barringtonia, Bambusa*
9 Billabong aquatics, *Nelumbo, Nymphaea, Nymphoides*

**Figure 7** Schematic vegetation transect across paleoestuarine plain
Inland of the saline mudflat is a grass and sedge-covered plain. Chenier ridges, where well-developed, contain a vegetation dominated by *Bombax ceiba*, *Pandanus spiralis*, *Morinda citrifolia*, *Thespesia populnea*, *Hibiscus tiliaceus*, *Syzygium suborbiculare*, *Trema* sp., *Ficus* spp., and various lianes. Elsewhere these ridges are low shelly accumulations, little higher than the surrounding plains, with grasses and are extensively burrowed by goannas. Many are the sites of Aboriginal middens and are of archaeological significance, or contain jungle fowl mounds (Baker 1981).

![Figure 8](image)

1 Subtidal mudflat
2 Intertidal mudflat
3 Mudflat with mangrove stumps
4 Seaward mangroves - *Avicennia*
5 Mixed mangroves - *Rhizophora*
6 Landward mangroves - *Ceriops, Avicennia*
7 Chenier, grasses
8 Succulent herbs, *Sarcocornia*, and grasses, *Sporobolus*
9 Grasses and sedges
10 Mangroves, *Avicennia*
11 Chenier, *Thespesia, Hibiscus, Eugenia, Trema, Bombax*

*Figure 8* Schematic vegetation transect across northern coastal plain (based in part upon unpublished description by Bateman, 1957, held in files of Water Resources Division, NT)
The plains have been invaded by a series of weeds. The most noxious is *Mimosa pigra* which forms a dense thorny thicket over about 2000 ha of the plains (Lonsdale 1988). As the tidal creeks extend inland, the distribution of mangroves is also increasing, with *Sonneratia lanceolata* and *Avicennia marina* being the first species to colonise further inland (Plate 6). *Sporobolus, Paspalum*, and the succulent halophytes are also rapidly invading the areas previously occupied by *Melaleuca*, but now intruded by saltwater.

![Plate 5](Image)

**Plate 5** Prominent mangrove fringe, 200 m wide and dominated by *Rhizophora stylosa*. Dead mangrove to the landward and *Sonneratia alba* and *Avicennia marina* seaward

### 1.2. Objectives of the study

There were three objectives to this study:

i) to describe and map the geomorphology of the Mary River floodplains, using methods developed during a similar study on the plains of the South Alligator River (Woodroffe et al 1986);

ii) to determine the chronology of Holocene environmental change on the Mary River plains, and to assess the reasons for change; and

iii) to assess the geomorphological potential for rehabilitation of the floodplains, including land management and physical works options.
The results of the study, which was carried out over a period of three years, are presented here. Chapter 2 describes the contemporary morphology and topography of the plains, based on the extensive survey data collected by the Land Conservation Unit of CCNT. Results of a detailed drilling program are summarised in chapter 3 and an interpretation of the chronological and stratigraphic development of the plains is presented. In chapter 4 recent changes, determined from aerial photography taken over the last 50 years, are described and preliminary observations on the hydrodynamic behaviour of the creek networks are outlined. Chapter 5 discusses likely future changes to the plains and the potential to control them.

Plate 6 Recent colonisation of mangroves (Sonneratia lanceolata) along the margins of Sampan Billabong, with Mimosa pigra in the background
2. MORPHOLOGY OF THE LOWER MARY RIVER PLAINS

The Mary River plains differ from the plains flanking the other major macrotidal rivers along van Diemen Gulf, the East and South Alligator and Adelaide Rivers (Table 1), primarily because there is not presently a major estuarine channel dominating the river mouth and hence there has been greater freshwater influence over the surface of the plains.

**Table 1. Areas of lowland plains and catchments of rivers draining to southern van Diemen Gulf**

<table>
<thead>
<tr>
<th>River</th>
<th>Coastal plain C (km²)</th>
<th>Estuarine plain E (km²)</th>
<th>Upland catchment U (km²)</th>
<th>U/C</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adelaide River</td>
<td>565</td>
<td>1100</td>
<td>6250</td>
<td>11</td>
<td>Diverted</td>
</tr>
<tr>
<td>Mary River</td>
<td>565</td>
<td>540</td>
<td>6530</td>
<td>12</td>
<td>Blocked</td>
</tr>
<tr>
<td>Swim Creek</td>
<td>45</td>
<td>70</td>
<td>320</td>
<td>7</td>
<td>Blocked</td>
</tr>
<tr>
<td>Carmor Plains</td>
<td>80</td>
<td>120</td>
<td>175</td>
<td>2</td>
<td>Blocked</td>
</tr>
<tr>
<td>Wildman River</td>
<td>90</td>
<td>275</td>
<td>2225</td>
<td>25</td>
<td>Open</td>
</tr>
<tr>
<td>West Alligator</td>
<td>20</td>
<td>210</td>
<td>1080</td>
<td>54</td>
<td>Open</td>
</tr>
<tr>
<td>South Alligator</td>
<td>90</td>
<td>915</td>
<td>10315</td>
<td>115</td>
<td>Open</td>
</tr>
<tr>
<td>East Alligator</td>
<td>145</td>
<td>945</td>
<td>8800</td>
<td>61</td>
<td>Open</td>
</tr>
</tbody>
</table>

2.1. Morphological provinces of the Lower Mary River plains

The same broad morphological provinces can be recognised on the Lower Mary River plains as those on the adjacent plains:

i) a coastal plain, developed mainly as a result of nearshore marine processes;

ii) a paleoestuarine plain formed, in a similar way to the estuarine plains of other rivers, through a combination of tidal and fluvial processes, but presently affected only by fluvial processes; and

iii) an alluvial plain, extending upstream of the paleoestuarine plain.

The coastal plain is divided from the paleoestuarine plain by a beach ridge or chenier which flanks the upland margin, and which, based upon data presented below, marks
the shoreline around 6000 years ago, and distinguishes the plain to the south (paleoestuarine plain) which has been deposited primarily by vertical accretion, from the plain to the north (coastal plain) which has built out by coastal progradation (gradual horizontal build-out). The paleoestuarine plain meets the alluvial plain at the upstream limit to tidal influence in the mid-Holocene. This occurs between the muddy floodplain at Black Fella Island, and the sandy alluvial fan at Clarke’s Crossing. Within these provinces a series of morphological units can be recognised; these are shown on the accompanying geomorphological map, and are described below in Table 2.

Table 2. Morphological units on the Mary River coastal and paleoestuarine plains

<table>
<thead>
<tr>
<th>Morphological unit</th>
<th>Definition</th>
<th>Inundation</th>
<th>Elevational range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal plain:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mangrove</td>
<td>Upper intertidal coast and creek bank</td>
<td>Flooded tidally</td>
<td>0.6–1.8m AHD</td>
</tr>
<tr>
<td>Saline mudflat</td>
<td>Upper intertidal and supratidal</td>
<td>Flooded infrequently by tides</td>
<td>1.8–2.2m AHD</td>
</tr>
<tr>
<td>Lower coastal</td>
<td>Low-lying depressions</td>
<td>Remains wet for &gt;5 months of the year</td>
<td>1.8–2.2m AHD</td>
</tr>
<tr>
<td>plain</td>
<td></td>
<td>Remains wet for &lt;5 months of the year</td>
<td>2.2–2.7m AHD</td>
</tr>
<tr>
<td>Levee</td>
<td>Higher parts of coastal plain</td>
<td>Rarely inundated, drains early in dry</td>
<td>2.4–3.1m AHD in</td>
</tr>
<tr>
<td></td>
<td>Flanking paleochannels</td>
<td></td>
<td>east, lower in west</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Remains wet for &gt;5 months of the year</td>
<td>&lt;2.1m AHD in east,</td>
</tr>
<tr>
<td>Paleochannel</td>
<td>Former tidal channels</td>
<td></td>
<td>&lt;1.7m AHD in west</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Remains wet for &gt;5 months of the year</td>
<td>not surveyed</td>
</tr>
<tr>
<td>Paleocreek</td>
<td>Former tidal creek</td>
<td>Rarely flooded</td>
<td>2.2–2.9m AHD</td>
</tr>
<tr>
<td>Chenier</td>
<td>Sandy/shelly ridge</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Paleoestuarine plain:

<table>
<thead>
<tr>
<th>Morphological unit</th>
<th>Definition</th>
<th>Inundation</th>
<th>Elevational range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper floodplain</td>
<td>Higher ground close to channels</td>
<td>Remains wet for &lt;5 months of the year</td>
<td></td>
</tr>
<tr>
<td>Lower floodplain</td>
<td>Low ground away from channels</td>
<td>Remains wet for &gt;5 months of the year</td>
<td></td>
</tr>
<tr>
<td>Paleochannel</td>
<td>Former channels</td>
<td>Remains wet for &gt;5 months of the year</td>
<td></td>
</tr>
<tr>
<td>Levée</td>
<td>Flanking paleochannels</td>
<td>Remains wet for &gt;5 months of the year</td>
<td></td>
</tr>
<tr>
<td>Backwater swamp</td>
<td>Depressions on plains margin</td>
<td>Remains wet for &gt;5 months of the year</td>
<td></td>
</tr>
<tr>
<td>with Melaleuca</td>
<td></td>
<td>Rarely inundated, drains early in dry</td>
<td></td>
</tr>
<tr>
<td>Open backwater</td>
<td></td>
<td>Remains wet for most of the year</td>
<td></td>
</tr>
<tr>
<td>swamp</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.1.1. Coastal plain

The coastal plain of the Mary River is a near-horizontal progradational plain which has built out as a result of the deposition of sand and mud in van Diemen Gulf. A series of morphological units can be recognised (Table 2), and are mapped on the accompanying geomorphological map.
Mangrove
This zone lies landward of a broad intertidal zone (see Figure 8), and represents a
distinct morphological unit, which continues up minor creeks as a littoral fringe, and is
also identifiable as a widespread stratigraphic unit, mangrove facies. The sediments
are bioturbated muds, usually with a thin oxidised layer overlying an anaerobic
sulphide-rich mud with abundant organic fragments. Mangroves do not yet occupy
the entire upper intertidal; they presently extend only part way along Sampan Creek,
but they are rapidly extending inland, having colonised Sampan Billabong in the last
two years. The most prominent mangrove forests are those along the coast, forming a
series of zones up to 200 m wide, with dead mangroves and stumps to landward, and
in places also to seaward (see Plate 5).

Saline mudflat
Landward of the mangrove zone there is often a saline mudflat. This is generally bare
of vegetation, but in places supports halophytes. It is subject to saltwater inundation
during only the highest tides. While this unit forms a distinct zone parallel to the
coast, there are also occurrences in isolated pockets across the plains especially in
areas where saltwater has intruded into formerly vegetated areas. The surface of the
saline mudflat dries between spring tides into polygonal cracks, and the surface often
develops a crumbly crust as clay particles flocculate into silt and sand-sized
aggregates.

Upper coastal plain
The upper coastal plain is a sedge-covered plain, ranging in elevation from 2.0–2.2 m
AHD (Australian Height Datum, see below) to 2.5 m AHD, and rarely inundated for
long periods during the Wet season.

Lower coastal plain
The lower coastal plain is lower than the upper coastal plain, generally at an elevation
less than 2.0 m AHD. It is covered by grasses and sedges and may remain wet for
several months beyond the late Wet season. Lower coastal plain merges gradually
into upper coastal plain, and, where there are no survey data, it may be difficult to
distinguish between the two.

Lower coastal plain with Melaleuca
This unit is similar to the lower coastal plain, and is distinguished not on
geomorphological grounds, but because it supports an open woodland of paperbark
trees (Melaleuca spp.). It is also low-lying, less than 2.0 m AHD, though much is
inaccessible and has not been surveyed. It remains wet for much of the year. A
particularly large stand of such Melaleuca occurs on the western margin of the Mary
River plains, representing one of the largest stands of coastal paperbark in the
Northern Territory.

Inland saline basin
This unit is similar to the lower coastal plain units described above, but is inundated
by saltwater and characterised by dieback of Melaleuca and other freshwater
vegetation.
Paleochannel
The paleochannels are low-lying areas which were formerly occupied by active tidal channels. Tapering of these indicates that most were estuarine, and their dimensions are similar to the larger estuarine channels which are found on the rivers to the west and east of the Mary River. Their upper surface is of low elevation, and some parts may remain wet throughout the year, or they may dry out and become saline mudflat. They have been found to be particularly susceptible to saltwater intrusion.

Paleocreek
Paleocreeks represent the courses of former tributary creeks feeding into paleochannels. They are generally low-lying, often with drier areas presumed to be levées, flanking them.

Levée
The paleochannels on the coastal plain are in many cases flanked by broad levées. Though these are barely recognisable as higher ground in the field, the detailed surveys described below indicate that they are critical in preventing direct saltwater flooding of the plains by overbank flow during the highest tides. The low relief of these features, 60–80 cm above surrounding plains, means that they are also difficult to detect on aerial photography, although they do appear to correspond to subtle changes of tone, presumably reflecting vegetation patterns on these drier sites. Levées represent some of the highest ground on the plains; in view of their subtle relief, their full extent may not be mapped on the accompanying map, but their recognition and maintenance will be important elements of the management of the plains.

Chenier/beach ridge
The coastal plain has built out gradually and the position of former shorelines is marked by a series of chenier and beach ridges. A chenier ridge is a sandy coastal ridge with shell and shell fragments (especially Anadara granosa), overlying muddy nearshore sediments. Such features mark a period of interruption of the normal muddy progradation of an estuarine or deltaic shore. A beach ridge, on the other hand, is comprised entirely of sand overlying bedrock, or a sandy substrate, which may have been deposited during only a brief interruption to a more continuous muddy progradation. The Mary River coastal plain is separated from the paleoestuarine plain by a sandy beach ridge, which in places overlies the upland bedrock substrate, but elsewhere may form a chenier. This beach ridge skirts discontinuously around the upland margin, and lies just seaward of Alligator Head. The former shoreline ridges fringing the coast along the northern margin of the coastal plain, overlie mud, or sandy mud of the plain and are cheniers, composed mainly of shell, although with shell leached from the more landward ridges. These ridges are discontinuous, narrow linear sandy and shelly occurrences, often with almost no topographic expression. Occasionally the sandy deposits are found cemented into gently seaward-dipping outcrops of beachrock. Augering has indicated that they can be several metres in subsurface depth.
2.1.2. Paleoestuarine plain

The paleoestuarine plain formed as a tidal floodplain flanking an estuarine channel or embayment. It terminates to the north at the constriction between Alligator Head and Shady Camp (Figure 3). Morphological units within this province are again distinguished by relative elevation and frequency of inundation.

**Upper floodplain**

There are a series of higher parts of the paleoestuarine plain that are flooded for only short periods during the year if at all. These are mapped as upper floodplain. Their elevation is less certain because surveys across these plains were not related to AHD; but it seems likely that their elevation ranges from around 2.5–2.6 m AHD near Shady Camp to 3.0–3.2 m AHD at Corroborrie and to around 4.0–4.3 m AHD near Black Fella Island.

**Lower floodplain**

Generally at greater distance from the main channels there are lower lying areas that remain flooded up to and into the Dry season. These are termed lower floodplain, and are about 30 cm lower than upper floodplain, showing a similar gradient along the valley axis.

**Lower floodplain with Melaleuca**

Some parts of the lower floodplain support open woodland of paperbark (*Melaleuca* spp.), and are mapped as a separate lower floodplain unit on the accompanying geomorphological map.

**Backwater swamp**

Re-entrants within the uplands, often receiving minor runoff from small creeks, are found at the margins of the plain. The higher parts of these backwater swamps are colonised by paperbark (*Melaleuca* spp.), and their surface tends to dry out for a month or two during the dry season.

**Lower backwater swamp**

Other areas within these same re-entrants remain wet for longer, and many are perennially wet. These are of lower elevation and contain aquatic vegetation and are mapped as lower backwater swamp.

**Paleochannel**

A series of paleochannels are recognisable within the paleoestuarine plain. They tend to be fairly uniform in width, and in many cases are occupied by the discontinuous sequence of linear billabongs that join up in the Wet season. The contrast in their morphology with those on the coastal plain reflects their origin, or recent occupation, primarily as fluvial channels, with little if any tidal influence. Although tidal flows have penetrated through the Alligator Head–Shady Camp constriction in the past, their influence is not preserved in the form of the channels that can be seen on the plains. Billabongs are fringed with shrubs and stands of *Pandanus*, *Cathormium* and *Barringtonia*. 
Levee
Broad levee features flank the paleochannels and are clearly higher than the land at greater distances from the channel. They dry out early in the Dry season and are vegetated by grass swards. There is insufficient survey data to indicate the amplitude or absolute elevations of levees in the paleoestuarine plain.

2.1.3. ALLUVIAL PLAIN

The alluvial plain occurs south of the paleoestuarine plain, and is composed of an alluvial fan-delta traversed by a series of incised creeks, within which sandy alluvial units are exposed. It lies outside the area of concern of this study.

2.2. Elevation of the Lower Mary River Plains

Absolute elevations across the plains, related to Australian Height Datum (AHD), are invaluable in that they indicate the 3-dimensional topography of morphological units, and allow a better assessment of vulnerability to saltwater intrusion by relating tidal data to the same datum. Observations of tide levels in Sampan Creek are shown in Figure 9, based upon tidal surveys on extreme high tides.

![Figure 9: Tidal curves for Darwin Harbour, and four locations up Sampan Creek, Mary River: mouth, Roonees Lagoon, S-bends, Shady Camp, for the period 5–8 April 1992. [For details of location see Table 7: Data: Water Resources Division, NT]
Australian Height Datum (AHD) approximates mean sea level. It is a datum surface throughout Australia calibrated to observed mean sea level at a series of primary tidal stations. Darwin is one of the stations where AHD was linked to MSL. However, it may not correspond exactly to mean sea level in van Diemen Gulf, as various tidal factors can elevate the mean water surface in the Gulf. A divergence between AHD and MSL has been observed at the mouth of the Mary River, and comparison of tidal curves recorded simultaneously in Darwin Harbour and at the mouth of the Mary River (Figure 9) indicates that mean tide level at the mouth of the Mary River is nearly 1 m above that in the Harbour. Figure 9 also demonstrates the progressive deformation of the tide (ie, increasing asymmetry and decreasing amplitude upstream) as it moves upstream (see hydrodynamics section for details).

The following discussion is based upon results of the survey program undertaken by the Land Conservation Unit of the CCNT (Figure 10). A number of topographic trends were indicated by survey results from the 1990 Dry season (Figure 11; David Smith, principal surveyor) and these have been validated and augmented by survey results from the 1991 Dry season (Figure 12; Ian Fulton, principal surveyor). Profiles north of Shady Camp have been closed either by surveying in both directions, or by surveying onto a permanent benchmark with a known reduced level. The data are considered accurate to a precision of \( \pm 5 \) cm; the plains themselves exhibit a local scale of microtopography, demonstrated by comparing adjacent spot heights on a profile, of the order of \( \pm 10 \) cm. In distinguishing broad differences across the plains it is, therefore, appropriate to differentiate at a vertical scale of 0.1 m.

The topography of a series of shore-parallel zones, including the coastal mangrove fringe, cheniers and saline mudflat, is shown on two shore-normal transects: profiles B (Figure 11) and M (Figure 12). Nearshore mudflats, extending seaward at a low gradient and exposed for 2–3 km at low tide, are colonised by mangroves at 0.6 m AHD on profile B and 0.9 m AHD on profile M. The elevational range of the mangrove fringe is 0.6–1.8 m AHD on profile B and 0.9–1.4 m AHD on profile M; this is a much narrower range than observed in Darwin Harbour (where the tidal amplitude is greater) or at the mouth of the South Alligator River, and probably reflects the narrower and more rapidly changing nature of the mangrove shoreline (mangrove stumps 50–100 m seaward of the present shoreline at B1 indicate that this section of the shoreline is actively eroding) along this part of the southern shore of van Diemen Gulf (see recent coastal change section). Mangroves occur up to 2.1 m AHD further to the east of Sampan Creek (I Fulton, pers. comm., 1992).

Cheniers occur along both profiles B and M. On profile M there are double ridges at the coast reaching 3.4 and 3.5 m AHD; a second chenier ridge at 0.6 km inland reaches 2.6 m AHD and a third at 2.2 km inland reaches 2.7 m AHD. This compares with heights of 2.5 m AHD at 1.2 km inland, 2.4 m AHD at 1.5 km inland and 2.9 m AHD at 2.9 km inland on profile B. None of these cheniers are particularly high considering that high tides presently reach at least 2.6 m AHD at the mouth of Sampan Creek and have been recorded up to 2.75 m AHD during the peak of the Wet season flood (D Williams, pers. comm., 1993).
Figure 10 Location of surveyed transects on the Mary River plains
Figure 11  Surveyed transects across the Lower Mary River plains showing morphological units. Surveys undertaken in 1990 by David Smith (L1–L2 by John Veal), Land Conservation Unit CCNT: Locations shown in Figure 10
Figure 12 Surveyed transects across the Lower Mary River plains showing morphological units. Surveys undertaken in 1991 by Ian Fulton, Land Conservation Unit CCNT; Locations shown in Figure 10.
Unvegetated saline mudflat occurs between the coastal mangrove fringe and the first chenier ridge at an elevation of 2.0–2.1 m AHD on profile B and up to 2.2 m on profile M. Sedgeland is present at elevations above 2.2 m AHD, forming what has been mapped as upper coastal plain, on both profiles B and M, while those areas near the coast and below this height (particularly on profile M), are generally prone to saltwater inundation.

On profile B, the height of the coastal plain decreases slightly with distance from the shore; behind the second chenier ridge the plain has a general elevation of 2.0 m AHD, decreasing behind the third chenier ridge to 1.8–1.9 m AHD, and continuing further south to vary between 1.9 and 2.1 m AHD. On profile M, much of the coastal plain is also in the range 2.0–2.1 m AHD, at least behind the third chenier, but there are extensive areas of upper coastal plain between 2.4 and 2.7 m AHD, between the second and third chenier ridges. These areas appear unusually high, the plains at M2 dropping back to an elevation of 1.9–2.1 m AHD. In at least one section this higher sedgeland may be related to an extensive chenier ridge which occurs to eastward (upon which borehole MRH7 is located) but has no surface expression as a distinct shell ridge on profile M.

Both profiles B and M cross a major meander in a paleochannel further south. On profile B the levée to the north of the paleochannel is about 650 m wide and rises to 2.4 m AHD; a similar elevation is found on the levée within the meander (B3), whereas there is a far less distinct levée form to the south of the paleochannel, rising to only 2.1 m AHD (Figure 11). The paleochannel itself remains relatively Wet well into the Dry season, contains abundant paperback, and has a surface elevation of around 1.4–1.7 m AHD to the north and 1.5–1.7 m AHD to the south. On profile M the levée is much more pronounced. It is more than 1 km wide and rises to 2.8 m AHD, flanking the paleochannel, to the north, within the meander and to the south of the paleochannel. The paleochannel surface is in the range 1.9–2.1 m AHD to the north and 1.9–2.0 m AHD to the south, similar to the elevation of the coastal plain away from the levées, suggesting relatively complete infill of the former channel. Small tidal creeks have incised to form deep narrow gutters, 0.3–1.5 m below the present surface of the paleochannel.

The survey data generally indicate that paleochannels, particularly those that carried major estuarine channels, are flanked by broad levées. This local, channel-specific topography masks the more general gradients across the plains, and has complicated the interpretation of the 1990 survey results (Figure 11). There is now such a network of survey lines across the plains (Figure 10) that it is possible to detect broad gradients across the plains.

Levées flanking the present Sampan Creek, but apparently deposited on the margin of the paleochannels, are particularly significant because they represent some of the highest ground on the coastal plain. Thus profile E11–E12 (Figure 11) rises from the upland margin from a height of 2.1–2.2 m AHD, across a middle section at 2.2–2.3 m AHD, onto a levée adjacent to Sampan Creek where it rises to 2.7 m AHD. The levée
is similar in form and height to that encountered within the survey transect from M2 to M3. This broad gradient is also demonstrated on profile E21 to E22 (Figure 11), which corresponds very closely to S1–S3 (Figure 12). Near the upland margin the plains are at 1.8–2.0 m AHD; in mid-profile the plains rise to 2.0–2.3 m AHD, and adjacent to the creek they rise to 2.7 m AHD.

The levée features which characterise the eastern plains range between 2.4 and 3.1 m AHD, and are significantly higher than those of the western plains, which range between 2.0–2.6 m AHD. Levées, where they occur, are typically 30–50 cm above the general coastal plain, while the paleochannel surface may be as much as 1.0–1.5 m below the top of the levée. Levée morphology is generally asymmetric with the highest elevation close to the channel, trending away, for widths of 600–1200 m.

Levées are prominent flanking the major estuarine paleochannels, but are not as distinct adjacent to the modern channel where it is not within a paleochannel, or where it reoccupies what appears to be a fluvial paleochannel (see paleochannel section). Thus on profile P near the western margin of Sampan Creek (Figure 12), the paleochannel between P2 and P3 does not have a distinct levée and rises to only 2.3 m AHD, compared with an elevation of 2.8 m AHD on the large paleochannel at M3, perhaps as a result of the proliferation of tidal creeks through this area.

At N3 there is little remaining of the levée. A narrow ridge 50 m wide and 2.2 m AHD has been incised by a small tidal creek, and breaching of this levée occurs at spring high tides. A more prominent levée rising to 2.4 m is found on the west bank of Sampan Creek at this site. Levées flanking Alligator Lagoon are of unequal size (Figure 12); between M5 and M6 the levée on the northern side is up to 2.5 m AHD while that to the south is less than 2.2 m AHD; between N2 and N3 it is 2.2 m AHD to the east and 2.5 m AHD to the west. Much of the area between Sampan Creek and Alligator Lagoon is low-lying and is salt-affected lower coastal plain.

Levées are also found flanking the paleochannel at Dead Fish Billabong, and these are 2.4 m AHD to the west and 2.6 m AHD to the east. There is not a distinct levée at the paleochannel at N7, but the levée on the west bank of the main channel at Shady Camp is 3.1 m AHD high, representing the highest point surveyed on the plains.

The 1991 survey results from the eastern side of the Mary River plains serve to illustrate that the general seaward-landward gradient is not pronounced, and that greatest topographic expression is in the upland margin to paleolevée cross-valley profile. Little variation in the elevational range of the latter is found with distance inland.

On the next profile south, profile S, the overall relief appears to have decreased (Figure 12). The plains adjacent to the upland margin occur over a range of 1.8–2.0 m AHD, but the levée, which is highest adjacent to the Alligator Lagoon paleochannel rather than the paleochannel presently occupied by Sampan Creek, reaches only 2.5 m AHD on its western side and 2.2 m AHD on its eastern side.
It would appear that when the influence of the levée-effect is removed, the coastal plain is generally in the range 1.9–2.0 m AHD, at least as far as 12 km from the coast; such elevations are encountered around B4 (profile B, Figure 11); at N5 (profile N, Figure 12); and between N1 and N2 (profile N, Figure 12).

A major levée fringes the western paleochannel (paleochannel C), and it is this which gives the appearance of a gradient with distance from the coast. Thus the points surveyed in 1990, fluctuating between 2.1 and 2.5 m AHD from A5 to C21, up to 2.6 m at D31, and 2.5–2.6 m at A7 are all influenced by the levée of this paleochannel (Figure 11). The plains away from this levée influence are much lower; thus C12 and C22 are 1.7 m AHD or lower, and around N5 the plains are only 1.8–2.0 m AHD.

The paleochannels converge towards the confined gap between Alligator Head and Shady Camp, and there appear to be few if any parts of the plain which are not influenced by levée convergence in this section. Plains elevations are characteristically 2.5–2.6 m AHD and around Shady Camp are 2.8–3.1 m AHD.

Elevations on the floor of paleochannels are more variable than the 1990 data had suggested and this reflects the extent of sediment infill. Whereas the western paleochannel is incompletely infilled and contains numerous open water stretches with an aquatic vegetation, and its elevations are low (1.6 m AHD south of A4; 1.4–1.7 m AHD north of B3, 1.5–1.7 m AHD south of B3, 1.4–1.8 m AHD at D11–D12; 1.6–1.8 m AHD at D21–D22 and 1.8–1.9 m AHD at D31–D32), paleochannels on the eastern side of the plains are better infilled and higher, but vary little. Thus near the mouth of Sampan the paleochannel at M3 is 1.9–2.1 m AHD and at P1 1.9–2.0 m AHD. Alligator Lagoon is 1.9–2.0 m AHD between M5 and M6 and at a similar elevation between N2 and N3. The paleochannel down which Tommycut Creek is reconnecting with Sampan, near N4, is also 1.8–2.0 m AHD. Along profile P the northern east-west paleochannel sequence has an elevation of 2.1–2.2 m AHD at P2; 1.7–2.0 m AHD near P3; 1.7–1.9 m AHD near R2; and 2.0–2.1 m AHD between P4 and P5 on Tommycut Creek.

Paradoxically, the eastern paleochannels are better infilled (ie, their surface is higher), and yet are more dissected and are more extensively reoccupied by the expanding tidal system, than the western paleochannel whose surface appears to be generally lower than other paleochannels. This western paleochannel has scarcely been influenced by saltwater intrusion although this may partly reflect the construction of barrages to protect the western paleochannel. Nor are the lowest paleochannels always the first to be invaded; at P3 a paleochannel with an elevation of 1.67 m AHD is not invaded, while the same paleochannel at P2, where it is nowhere less than 2.0 m AHD, has well-established tidal creeks.

The survey data provides a valuable indicator of the surface elevation at which saltwater intrusion has occurred. Despite early results, which suggested a high degree of variability in the elevation at which salinisation was taking place, there is actually a remarkable consistency in the elevation at which salt intrusion is occurring. Near the coast saltwater is intruding into areas (at least on profile M) up to an elevation of
2.2 m AHD; this rapidly drops to about 2.1 m at 2 km inland, and is around that level where profile P crosses Tommycut Creek. Over much of the rest of the plain elevations below 2.0 m AHD are generally prone to salt intrusion, although this level decreases with distance inland, being 1.9 m AHD at N5 and 1.8 m around N7.

Survey data from the Red Lily Lagoon area, at the western extension of the Narrows paleochannel system, provide some of the lowest values for a paleochannel environment with heights between 1.6–1.7 m AHD. Saltwater incursion has already begun, with creek expansion into the Red Lily Lagoon paleochannel (at A7, N7). The potential for further rapid saltwater intrusion in this area is a major concern and is discussed further in chapter 5.

There are significant areas that are below the elevation at which saltwater is intruding, and which might be expected to be salt-affected, but are not. These include a backwater swamp in the area of N1, which is around 2.0 m AHD, but is protected by a beach ridge which reaches 2.9 m AHD; areas below 2.0 m AHD to the east of the ridge are salt-affected.

There is also a gradient in the elevation at which areas are being salt-intruded with distance away from the major creeks — Tommycut and Sampan Creeks — such that saltwater invades higher areas adjacent to these creeks, than it does upstream along tributary creeks. This presumably results from the hydraulic gradient necessary for tidal water to penetrate great distances over horizontal surfaces. It can be seen in a detailed assessment of salt-affected areas along profile P1–P8. Highest values are at Tommycut 2.06 m AHD between P4 and P5, and at Sampan 2.15 m AHD at P2. With distance away salt only affects lower areas (ie, 1.96 m AHD P5–P6; 1.93 m AHD P6–P7). Saltwater intrusion is occurring at lower elevations in the inland saline basin, being at 1.7 m AHD at C22. Little is known about the elevation of the extensive Melaleuca area (lower coastal plain with Melaleuca) to the west of the Mary River coastal plain, as it is largely inaccessible. However, it is presumably below 2.0 m AHD which is the elevation typical of the area near B4. It is not inundated by saltwater at present largely because saltwater has not found a route into it, rather than because it is above the peak high tides.

Where the plains surface is below high tide level it is not necessarily inundated by sheet flow of saltwater, but by a progressive wetting front. Tidal waters can be observed progressing across a saline mudflat with successively higher tides up to and often shortly beyond spring high tide. Saltwater incursion is greater on the higher of the two high tides in a day (depending upon the degree of diurnal inequality); the next day the same high tide will be slightly higher, and rapidly reoccupies the wetting front of the previous day, so that water percolates through cracks in the desiccated mudflat extending that wetting front further. This percolation (the tide may move quite quickly through the larger cracks) ceases when slack water has passed in the main creek, and there is no longer a head to maintain the advance of the wetting process. On the following day the now larger wetting front is again rapidly reoccupied and further advanced.
Thus it is not just the gradient of the plains which determines inundation, but also the speed at which the desiccated plains surface may be rewetted. The clays remain moist, and in a more dispersive state between successive high tides on separate days, often for some days past the highest spring tide, but this rewetting loses impetus once the height of the high tide drops sufficiently.

The topography of the plains serves to emphasise their vulnerability to salt-water intrusion. The tidal creeks, which have expanded with such rapidity between Tommecut and Sampan, and around the western margin of Tommecut, appear to have invaded the lowest-lying areas. Much, but not all, of that central area which is below 2.0 m AHD near the coast, and below 1.8 m AHD inland has been affected by salt. This is not, however, the only area where creeks have expanded, nor the only explanation of creek expansion. The plains between N7 and N9 are 2.5–2.7 m AHD, well above the level of high spring tide incursion, however in recent years a number of tidal creeks have established in the area and are cutting back, threatening to by-pass the Shady Camp Barrage and introduce saline water to the paleoestuarine plains to the south.

Paleochannels, themselves often some of the lowest-lying of topography, are preferentially invaded by the expanding tributary network (Plate 7). Presumably their sediments, which appear generally finer-grained though limited sediment size data do not demonstrate this convincingly (see Figure 16), are more easily eroded.

Plate 7 Preferential tidal creek extension through palaeochannels; gradual colonisation of creek banks by mangroves evident in background
As a consequence the expanding tidal system is flanked by levées, themselves depositional features from a much earlier and rather different environmental setting. The high water mark reaches an elevation which would inundate large areas of the plains if there were not levées in between. It is remarkable that through reoccupation of former channel courses Sampan and Tommycut Creeks now follow a narrow corridor of significantly higher ground through generally low-lying plains which would be susceptible to flooding were it not for the natural levées within which the creeks are contained.

In the area to the north of Shady Camp there is an increase in the gradient of the plains as a result of an amalgamation of levées which give the plains a generally higher elevation than is characteristic at this distance from the coast.

Although Shady Camp is an area of high ground, with a high levée to its west, the survey from Alligator Head to Shady Camp (L1–L2, Figure 11; John Veal, principal surveyor) indicates that much of the adjacent plains surface is considerably lower. Parts are only 2.0–2.1 m AHD, and there are numerous paleochannels indicating that past river courses have occupied different routes to the sea through this narrow constriction. The billabongs remain water-filled throughout the year, and surveys of the elevation of their floors indicate that several are around 1.3 m AHD. These alternative routes through the Alligator Head-Shady Camp constriction are low-lying and thus vulnerable to saltwater intrusion. Because they are not confined by significant levées, they would also present far greater challenges to saltwater containment than the present course of the Mary River through Shady Camp Billabong, in the event that saltwater gained access to them, because they are not confined by such distinct levées.

2.3. Summary

1. The plains of the Lower Mary River can be divided into three morphological provinces: a coastal plain, developed as a result of nearshore and marine processes; a paleoestuarine plain, developed through combined tidal and fluvial influence, but no longer experiencing any estuarine processes; and an alluvial plain which occurs upstream of the paleoestuarine plain. Within these provinces morphological units can be recognised and are mapped on the accompanying geomorphological map.

2. The coastal plain contains a mangrove zone which characterises the upper intertidal area of the coast and riparian fringes, and a saline mudflat which occurs landward of the mangroves in areas inundated by the highest spring tides. Much of the area is upper coastal plain and is not inundated by floodwaters for more than a few weeks of the year. The lower-lying parts are lower coastal plain, those with *Melaleuca* have been mapped as a separate unit, while those which have been subject to dieback as a result of saline intrusion are mapped as inland saline basin. Paleochannels and paleocreeks are identified often flanked by levées. Former shorelines are marked by cheniers or beach ridges.
3. The paleoestuarine plain can be similarly divided into upper floodplain which is flooded for only a short period of each year, and lower floodplain, and lower floodplain with *Melaleuca*, which are inundated for longer. Within re-entrants there are backswamps, often dominated by *Melaleuca*, which remain Wet for much of the year, and lower backwater swamps which are often perennially Wet and dominated by aquatics. Paleochannels on the paleoestuarine plain are also flanked by levées.

4. Morphological units are defined primarily on the basis of elevation and their present susceptibility to tidal influence. Levelling has shown that much of the coastal plain is below the elevation which saltwater reaches at the coast (at the mouth of Sampan Creek the high water rarely exceeds 2.5 m AHD in the Dry season but reached 2.75 m AHD during the 1992 Wet season flood). At present the elevation of the area affected by saltwater decreases with distance upstream (reflecting the decrease in the height of high water upstream). There is also a decrease in the elevation at which an area is affected by saltwater up tributaries away from the main channels. Tidal waters flooding across a near-horizontal plain or mudflat inundate the surface by progressive reoccupation of a wetting front on successive high tides.

5. The coastal plain is at an elevation of around 2.0 m AHD over much of its area, with substantial areas of lower coastal plain at elevations below this. Saltwater intrusion is occurring primarily via paleochannels, the surfaces of which are generally below 2.0 m AHD. This pattern of intrusion is often constrained within the paleochannels by levées which prevent the direct inundation of the adjacent lower coastal plain despite it frequently being at a lower elevation than that reached by the highest tides in the headwaters of the expanding tidal creek network. Where a breach occurs in the levées, the lower coastal plain becomes particularly vulnerable to saltwater intrusion.
3. HOLOCENE DEVELOPMENT OF THE LOWER MARY RIVER PLAINS

The plains of the Lower Mary River are Holocene in age having been deposited during the last 10,000 years. The Holocene, together with the Pleistocene, comprises the Quaternary, an era covering the last two million years and one dominated by the waxing and waning of polar ice sheets. Although this period of marked climate change at high latitudes has been accompanied by some changes in climate in tropical Australia, including cooler temperatures and increased aridity during glacial phases (Webster & Streeten 1978; Kershaw 1983), the major impact on the Mary River system is likely to have been from the associated variations in sea level.

3.1. Quaternary sea level change

The volume of the world’s oceans has fluctuated as water has been incorporated into polar and high-latitude ice sheets, and then subsequently melted. A record of these fluctuations can be reconstructed from oxygen-isotope analyses of foraminifera in deep-sea cores. Figure 13 indicates the pattern of sea level fluctuations derived from such cores, calibrated against radiometrically dated coral-reef shorelines preserved on the rapidly uplifting Huon Peninsula of northern Papua New Guinea (Chappell & Shackleton 1986). The sea was at a level close to, or slightly above, present level at the peak of the last interglacial, 125,000 years BP. Since that time it has fluctuated through a series of progressively lower oscillations, until the peak of the last ice age (about 18,000 years BP on a radiocarbon timescale, shown to be around 21,000 years BP by TIMS uranium-series dating; Bard et al 1990). Sustained ice melt after the last glaciation has resulted in rapid sea level rise (the post-glacial marine transgression) until about 6000 years BP (Chappell & Polach 1991). There has been little further ice melt since 6000 years BP, but the pattern of sea level change over this period has differed from one part of the world to another as a result of different responses from the crust and upper mantle to the redistribution of ice and water loads (this is known as glacio- and hydro-isostasy, respectively). Whereas in parts of the New World the sea appears to have continued to rise at a decelerating rate relative to the land, around the Australian coastline there has been a slight fall of sea level, over the last 6000 years (Thom & Chappell 1975; Nakada & Lambeck 1989).

In Northern Australia the shoreline has undergone rapid horizontal translation in association with these vertical movements. A schematic cross-section of the sea floor of the Arafura Sea and van Diemen Gulf is shown in Figure 13, based on Jongsmma (1974). While the ocean volume at the peak of the last glaciation appears to have been less than at present by about 120 m (Fairbanks 1989), radiocarbon dates from Northern Australia suggest that the sea was 150–165 m below present at 17,000–18,000 years BP (Jongsma 1970; Veeh & Veevers 1970). At that time the shoreline was 200–300 m north of its present location.
Figure 13 Upper: pattern of sea level change over the last 240 000 years (after Chappell & Shackleton 1986). Lower: schematic cross-section across van Diemen Gulf and the Arafura Sea showing offshore topography and sediments (based on Jongsma 1974)

The floor of the Arafura and Timor Seas also preserves evidence of former shorelines at lower sea level (summarised in Woodroffe & Mulrennan 1991).

The approximate location of the shoreline 18 000 years BP and 10 000 years BP is shown in Figure 14 (based on the 150 m and 30 m isobaths, respectively). The extensive coastal and estuarine plains of the southern shore of van Diemen Gulf are underlain by muds laid down largely under mangrove forests (Woodroffe et al 1985, 1986, 1989, 1993). Radiocarbon dating of mangrove remains indicates a broad envelope within which sea level has changed during the Holocene (Woodroffe et al 1987) and is shown in Figure 14. The sea reached its present level at around 6000 years BP; since then it appears to have been relatively stable, with no clear evidence to suggest that it was higher than present, as has been shown for elsewhere in Australia. It may have been up to 1 m above present level (as suggested on Cobourg peninsula, Woodroffe et al 1992), but the details of this period of relatively little change are difficult to decipher for this region because of problems associated with the interpretation of mangrove remains relative to sea level, and because the tidal range is so large relative to the net change (Woodroffe & Mulrennan 1991).
Figure 14 a: Approximate shorelines 18,000 and 10,000 years BP (based upon 150 m and 30 m isobaths); b: Details of sea level envelope reconstructed for the last 8000 years based on radiocarbon dates on mangrove remains from the South Alligator River plains (after Woodroffe & Mulrennan 1991)
It is within the context of this pattern of sea level change that the evolution of the coastal and estuarine plains of the Mary River must be viewed. Detailed stratigraphy and radiocarbon dating of sediments from the plains of the South Alligator River have enabled the refinement of a model for the geomorphological development of the tidal river and plains. Three major phases have been suggested: a transgressive phase (prior to 6800 years BP); a big swamp phase (6800–5300 years BP), and a sinuous/cuspate phase (since 5300 years BP). During the transgressive phase, rising sea level inundated a previously fluvial valley, replacing terrestrial vegetation with mangrove forests. The subsequent big swamp phase coincided with sea level stabilisation, and was characterised by widespread mangrove forests throughout the estuarine plains. These mangrove forests underwent a succession from frequently inundated Rhizophoraceous communities to less frequently inundated, more landward communities dominated by *Avicennia*, eventually replaced by grass and sedge communities typical of freshwater wetlands. During the sinuous/cuspate phase the Dry season tidal river has been confined within river levées and channel banks. In the case of the South Alligator, the river was initially a sinuous, meandering channel which actively migrated through sedimentation of point bars and erosion of concave river banks. As a result of meander cutoffs, since 2500 years BP, the middle reaches of the channel have adopted a cuspate form. Cuspate sections can also be seen on other north Australian rivers and appear to reflect a particular hydrodynamic condition of the fluviotidal flow (Chappell & Woodroffe 1985; Vertessey 1990).

3.2. Stratigraphy of the Lower Mary River plains

The interpretation of the pattern of Holocene sedimentation of the Mary River plains is based on the stratigraphy of drillholes within the plains. The location of drillholes is shown in Figure 15 and includes hand augered holes, drill probes undertaken with Gemco HP7, and drill probes and continuous cores undertaken with a Jacro 350 rotary rig (Plate 8). Detailed core logs of drillholes are presented in the Appendix.

The broad pattern of Holocene sedimentation of the Mary River plains resembles that of the South Alligator plains, despite the present absence of a large tidal river within the former. The plains comprise mid-Holocene mud, and overlie either pre-Holocene lateritised pebbly gravels or quartz sands, which may be a subsurface expression and continuation of the modern alluvial plain. The pre-Holocene surface is encountered at depths of 6–9 m below mean sea level in cores from the plains (Table 3). This relatively horizontal surface was presumably exposed as the valley floor, when the sea was lower during the last glacial advance. We note that this surface is rather higher than the equivalent surface on the South Alligator River, where it appears to be around 12 m below AHD; the Adelaide River, based on only a couple of drillholes, seems to have a pre-Holocene surface at a similar depth to that on the Mary River.
Table 3. Depth pre-Holocene sediments encountered in cores on the coastal and paleoestuarine plain

<table>
<thead>
<tr>
<th>Drillhole</th>
<th>Depth to pre-Holocene (m AHD)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRH38</td>
<td>−9.0</td>
<td>Coastal plain</td>
</tr>
<tr>
<td>MRH39</td>
<td>−8.3</td>
<td>Coastal plain</td>
</tr>
<tr>
<td>MRH41</td>
<td>−6.7</td>
<td>Coastal plain</td>
</tr>
<tr>
<td>MRH45</td>
<td>−6.0</td>
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<tr>
<td>MRH47</td>
<td>−7.9</td>
<td>Coastal plain</td>
</tr>
<tr>
<td>MRH51</td>
<td>−6.9</td>
<td>Paleoeastuarine plain</td>
</tr>
<tr>
<td>MRH57</td>
<td>−7.5</td>
<td>Paleoeastuarine plain</td>
</tr>
<tr>
<td>MRH53</td>
<td>+1.1</td>
<td>Paleoeastuarine plain</td>
</tr>
<tr>
<td>MRH55</td>
<td>+1.2</td>
<td>Paleoeastuarine plain</td>
</tr>
</tbody>
</table>

Most of the plains are underlain by bluish-grey mud. The upper surface is generally dark grey, polygonally-cracked mud, enriched with the organic remains of roots. At depths of between 30 cm and 220 cm there is an oxidised zone within which the muds are pale grey to orange, often with streaky mottles. These contain occasional

![Plate 8 Jacro 350 rotary rig taking continuous cores from the paleoestuarine plain south of Shady Camp](image)
carbonate nodules and abundant jarosite (a yellow, buttery compound resulting from the oxidation of pyrite). The transition from the oxidised zone into the underlying bluish-grey muds is gradual and consists of a decrease in the frequency of oxidation mottles.

The pronounced colour changes with depth reflect overprinting of the initial sediment by the pattern of oxidation and reduction which is primarily determined by water table fluctuations. This oxidation/reduction overprinting obscures the environment under which the sediment was deposited. Detailed study on the South Alligator plains indicated that several analyses can offer an insight into the former environment of deposition. The major analyses are the geomorphology of the plains surface; sediment size characteristics; total salts content of the sediment; radiometric dating of macroscopic remains, including both wood and shell; and microfossil spectra, particularly pollen analysis.

3.2.1. Stratigraphic analyses

Sediment size analysis
Grain size characteristics of selected cores were examined using a Horiba Capa rapid sediment size analyser. Sediments are reported here in terms of sand (>63 μm fractions) and mud, where mud comprises both silt (2–63 μm) and clay (<2 μm).

The sediments are primarily mud-sized; sand content is low, generally less than 20%. The muds are dominated by silt, which typically comprises up to 60%. Silt and fine sand dominate channel fill, at least in MRH26 which was analysed in the most detail, and these channels do not appear to be infilled primarily with clays settled from suspension as interpreted for paleochannels on the South Alligator plains. Figure 16 summarises grain-size characteristics of selected cores from the plains; the significant presence of silt-sized particles on the Mary River can be seen.

Shell content
Shells are found most frequently in drillholes from the coastal plain, and their presence is useful in distinguishing coastal plain sediments from those sediments deposited in the paleoestuarine plain. Whole shells and shell hash are especially common below 2 m; for example, they are generally abundant in the lower par, below 190 cm in probe MRH38, below 180 cm in MRH39 and below 170 cm in probe MRH41. MRH43 has a lens of shell hash at 170–180 cm and a concentration of shell fragments below 450 cm. Species included Anadara granosa, Cerithidea and other ceriths, and species in the families Trochidae, Turitellidae, Mactridae and Cardiidae. This shell assemblage is characteristic of a shallow subtidal or intertidal environment, although ceriths may also be found in mangroves and can thus occur upstream on tidal rivers.

Radiocarbon dating
An indication of the absolute age of organic materials can be obtained by radiocarbon dating. Dating involves determining the amount of the radioactive 14C isotope remaining in the sample. It presumes that the initial concentration of 14C relative to 13C of the sample at death is known, and that the sample has behaved as a closed
Figure 15 Location of drillholes on the Mary River plains
system with respect to these carbon isotopes since death. The half-life of radiocarbon is taken as 5700 years. Samples were submitted to the Radiocarbon Dating Laboratory of the Australian National University (Gupta & Polach 1979), with some samples also submitted to Beta Analytic in Florida, three of which have been dated by accelerator mass spectrometry (AMS). Radiocarbon dates are listed in Table 4, and each age is given with a standard error that is a measure of counting reliability and background levels. Ages are quoted in radiocarbon years BP (before present, though actually ages are given as before 1950 by convention). Radiocarbon years are not the same as solar years, but calibrations are available determined from tree ring chronology and more recently from comparative precision uranium-series dating of radiocarbon dated coral samples (Bard et al 1990). Dates on wood and shell are not directly comparable because shell samples generally require an 'environmental correction' for ocean reservoir effect (ie, the shells are taking carbon from seawater which has a lesser $^{14}$C/$^{13}$C ratio than the atmosphere). While a value of 450 ± 35 years is the correction generally applicable in Australia, and would usually be subtracted from the measured age, midden shells dated from the South Alligator have on a number of occasions given ages younger than this (Woodroffe et al 1986).
This environmental correction appears to be an inappropriate value for all shell species in the estuarine settings under study, and in this study no environmental correction has been applied to the dates.

Table 4 Radiocarbon dating results from the Lower Mary River plains

<table>
<thead>
<tr>
<th>Lab no</th>
<th>Field code</th>
<th>Material</th>
<th>Drillhole</th>
<th>Depth (cm)</th>
<th>Coordinates</th>
<th>Radiocarbon date years B.P.</th>
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<tbody>
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<td>MRH 9</td>
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<td>HM 044377</td>
<td>1960 ± 200</td>
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<tr>
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<td>MRH 6</td>
<td>Mangrove wood</td>
<td>MRH 6</td>
<td>230</td>
<td>HM 034424</td>
<td>600 ± 270</td>
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<tr>
<td>6653</td>
<td>MRH 5/8</td>
<td>Organic fragments</td>
<td>MRH 5</td>
<td>245</td>
<td>GM 891011</td>
<td>5330 ± 210</td>
</tr>
<tr>
<td>6654</td>
<td>MRH 5/10</td>
<td>Organic fragments</td>
<td>MRH 5</td>
<td>305</td>
<td>GM 891011</td>
<td>5500 ± 260</td>
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<td>6655</td>
<td>MRH 4/12</td>
<td>Shell (Anadara)</td>
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<td>GM 960192</td>
<td>6650 ± 430</td>
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<td>MRH 10</td>
<td>Shell</td>
<td>MRH 10</td>
<td>330</td>
<td>HM 053387</td>
<td>5170 ± 200</td>
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<td>Shell</td>
<td>MRH 6</td>
<td>260</td>
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</tr>
<tr>
<td>7140</td>
<td>MA 8</td>
<td>Nodular carbonate</td>
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<td>7143</td>
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<td>—</td>
<td>GM 953212</td>
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<tr>
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<td>GM 881074</td>
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<tr>
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<td>HM 015398</td>
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<tr>
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<td>GM 904277</td>
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<td>GM 924243</td>
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<td>7165</td>
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<td>MRH 38</td>
<td>560</td>
<td>GM 856402</td>
<td>4690 ± 210</td>
</tr>
<tr>
<td>7726</td>
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<td>MRH 39</td>
<td>950</td>
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<td>450</td>
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<td>Wood</td>
<td>MRH 49</td>
<td>945</td>
<td>GM 953126</td>
<td>5470 ± 240</td>
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### Table 4 Radiocarbon dating results from the Mary River plains (continued)

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<th>Lab no*</th>
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<th>Material</th>
<th>Drillhole</th>
<th>Depth (cm)</th>
<th>Coordinates</th>
<th>Radiocarbon date years B.P.</th>
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<td>7737</td>
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<td>MRH 52.6</td>
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<td>GM 878942</td>
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<td>MRH 50.4</td>
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<td>GM 975122</td>
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<td>MRH 58</td>
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<td>GM 855067</td>
<td>modern</td>
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<td>Midden shell</td>
<td>MRH 59</td>
<td>surface</td>
<td>GM 835270</td>
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<tr>
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<td>River bank</td>
<td>—</td>
<td>GM 940395</td>
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<td>Shell</td>
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<td>GM 939327</td>
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<td>Wood</td>
<td>River bank</td>
<td>—</td>
<td>GM 947347</td>
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<tr>
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<td>Carbonate nodule</td>
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<td>—</td>
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<td>5350 ± 200</td>
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<tr>
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<td>River bank</td>
<td>—</td>
<td>GM 953366</td>
<td>2640 ± 60</td>
</tr>
<tr>
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<td>Organic fragments</td>
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<td>135</td>
<td>GM 788337</td>
<td>3640 ± 70</td>
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<td>55846</td>
<td>MRH 60</td>
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<td>215</td>
<td>GM 910251</td>
<td>3390 ± 100</td>
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<tr>
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<td>MRH 61</td>
<td>140</td>
<td>GM 877326</td>
<td>3340 ± 70</td>
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<td>55848</td>
<td>MA 71</td>
<td>Chenier shell</td>
<td>Pit</td>
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<td>GM 974035</td>
<td>2220 ± 70</td>
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<td>55849</td>
<td>MA 70A</td>
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<td>50</td>
<td>GM 975407</td>
<td>1030 ± 60</td>
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</tbody>
</table>

* Four digit laboratory number indicates sample dated at the Australian National University Radiocarbon Dating Laboratory; five digit laboratory number indicates sample dated at Beta Analytical (55845–7, AMS dates).

It is also important to recognise that the radiocarbon dates represent the time of death of the organism, and not the time of its deposition. Thus individual shells may have been reworked several times after their death before being deposited in a chenier ridge. Dates therefore are not always accurate indicators of the age of landform units. Similarly dates on wood represent the age at which it died; wood may have floated around the creek systems or offshore before being deposited; even stumps which are growing in their place of growth are not always clear indicators of the form of the plain. Thus, at present, mangroves grow along creeks at considerable distances from the open coast, or from the main tidal channel, and are not just indicators of the intertidal zone at the immediate coast.

**Pollen analysis**

Pollen analysis shows the concentration of different pollen grains at depth increments through cores. This in turn reflects the vegetation and the change in vegetation over time through the period of sedimentation. Although pollen analysis is generally used to aid paleoclimatology through reconstruction of regional vegetation assemblages, it has been used successfully in estuarine environments to examine changes in local vegetation (Chappell & Grindrod 1985; Grindrod 1988). Pollen can be identified to
family level, and in some cases to genera. *Rhizophora* pollen is generally larger than
the pollen of *Ceriops* and *Bruguiera* in the same family, but when size is not
sufficiently distinct to decipher between *Rhizophora* and *Ceriops/Bruguiera*, pollen of
that family has been labelled as Rhizophoraceae id. Pollen spectra can be interpreted
to reconstruct the relative balance between mangrove wetlands and freshwater
wetlands (dominated by grasses sedges and paperbark trees). In addition pollen
provides some indication of mangrove species dominance. For instance, modern
pollen rain studies in the South Alligator wetlands have indicated that *Rhizophora*
pollen is abundant and often exceeds 70% of total pollen beneath stands of
*Rhizophora*, and where pollen spectra from cores approach this level of abundance it
is considered that a *Rhizophora*-dominated, and hence frequently-flooded mangrove
forest persisted (Chappell & Grindrod 1985).

**Salt content**
Almost all of the plains are underlain by saline muds. Salt concentration was
measured by leaching salt from dried sediment samples and determining total salts in
the sediment as KCl equivalent using a conductivity meter. Salt concentrations on the
coastal plain vary between 11 000 and 24 000 ppm, throughout cores, with occasional
excursions up to 44 000 ppm. Converting these to pore water salinities is difficult
because it is highly dependent upon moisture content. For example, pore water
salinities on drill samples collected in 1990, when compared with similar samples
collected in 1991, were found to be too high because the cores had dried out before
laboratory analysis. Salinity values in the range of 18–28 ppt are typical for muds
underlying the paleoestuarine plain. Considerably lower salt contents, 5000 to 9000
ppm in the upper metre of these cores, support the argument that the upper part of the
paleoestuarine plain, ie, the floodplain clay unit, was deposited under freshwater
conditions.

**Moisture content and organic content**
Moisture and organic contents were also measured on selected cores. Moisture
content was determined from wet and oven-dried weights of sediment samples, while
organic content was determined by weight loss on ignition in a muffle furnace at
600°C. The resultant values do not show any particular trend. Moisture content is
high, usually 30% to 50% of wet weight, and the organic content, determined by
weight loss on ignition is 7% to 15%, ranging up to 20% in some of the more woody
mangrove facies.

3.2.1. **Paleoestuarine plain development**

The sediments which directly overlie the pre-Holocene surface were deposited as the
sea level rose and as marine waters inundated the prior embayment about 7000 years
ago. This is indicated by radiocarbon dates on a basal bluish-grey mud, rich in
organic fragments, shown by pollen analysis to be mangrove-dominated. Radiocarbon
dates on this basal mangrove facies, representing the mangrove shoreline that existed
as sea level rose and first flooded this pre-Holocene surface, are given in Table 5.
**Table 5.** Radiocarbon dates on transgressive mangrove facies at the base of drillholes

<table>
<thead>
<tr>
<th>Drillhole</th>
<th>Depth (cm)</th>
<th>Radiocarbon date (years BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRH47</td>
<td>860</td>
<td>7030 ± 220</td>
</tr>
<tr>
<td>MRH25</td>
<td>850</td>
<td>7080 ± 140</td>
</tr>
<tr>
<td>MRH48</td>
<td>900</td>
<td>7290 ± 160</td>
</tr>
<tr>
<td>MRH26</td>
<td>980</td>
<td>6770 ± 240</td>
</tr>
</tbody>
</table>

This phase of sea level rise ended in deceleration and eventual stabilisation of sea level by around 6000 years BP. This is reflected in widespread mangrove forests within adjacent river valleys during a phase that has been termed the 'big swamp' (Woodroffe *et al* 1985). This big swamp phase is identifiable in the stratigraphy of the plains south of Shady Camp, and the Shady Camp–Alligator Head outcrops of the uplands form a constriction which roughly indicates the limit of the 6000 year shoreline. The stratigraphy and the radiocarbon dates which support this interpretation are shown in Figure 17.

South of Shady Camp, big swamp mangrove facies have been identified in a number of cores, both by radiocarbon dating, and by pollen analysis. These are overlain by alluvial floodplain clay, overprinted by heavy oxidation at 50–150 cm depth. Radiocarbon dates fall in the range 6790 to 5330 years BP (Table 6), reflecting the range of ages identified on the plains of the South Alligator River. It appears that the big swamp phase on the Mary River was contemporaneous with that of the South Alligator and other tidal rivers in the region (Woodroffe *et al* 1993). A date of 3920 ± 270 years BP from 265 cm in MRH12 may suggest that mangroves persisted in the paleoestuarine plain for some 2000 years after sea level stabilised, and perhaps for more than 1000 years longer than on the South Alligator. However, there are only localised sites at which this persistence is indicated, and these may well relate to local creek bank environments, so that mangroves may have disappeared from the bulk of the plains at a similar time on the Mary to the decline of mangrove forests on the South Alligator (Woodroffe *et al* 1985; Chappell & Thom 1986). Radiocarbon dates from MRH57 are anomalous and stratigraphically reversed: 7030 ± 160 years BP at 450 cm and 4150 ± 200 years BP at 740 cm. If these ages were encountered the other way around they would support the proposed model; possible switching of samples has not been detected, and these dates have been discounted.

The paleoestuarine plain appears to have formed almost entirely through vertical accretion, initially rapidly under mangrove forests. The rate of sedimentation may have been up to 10 mm/yr. Sedimentation slowed, however, after sea level stabilisation around 6500 years BP, with tidal inundation and luxuriant mangrove forest perhaps persisting locally until 4000 years BP, but then being replaced by freshwater wetlands. Vertical sedimentation has been much slower under the freshwater wetlands, averaging no more than 0.5 mm/yr, and probably being much less.
Figure 17 Distribution of proven and inferred mangrove facies (deposited in big swamp phase), and coastal plain, showing radiocarbon results, and a schematic longitudinal profile of the Mary River, indicating stratigraphy; tentative isochrons marking progradation of the western plains are shown (from Woodroffe et al 1993)
Table 6. Radiocarbon dates on mangrove facies of big swamp age from the upper part of cores on the paleoestuarine plain

<table>
<thead>
<tr>
<th>Drillhole</th>
<th>Depth (cm)</th>
<th>Radiocarbon date (years BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRH52</td>
<td>300</td>
<td>6790 ± 400</td>
</tr>
<tr>
<td>MRH56</td>
<td>310</td>
<td>6540 ± 200</td>
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<tr>
<td>MRH32</td>
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<td>6130 ± 90</td>
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<tr>
<td>MRH51</td>
<td>730</td>
<td>5780 ± 140</td>
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<td>MRH53</td>
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<tr>
<td>MRH05</td>
<td>305</td>
<td>5500 ± 260</td>
</tr>
<tr>
<td>MRH05</td>
<td>245</td>
<td>5330 ± 210</td>
</tr>
<tr>
<td>MRH30</td>
<td>350</td>
<td>5430 ± 340</td>
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</tbody>
</table>

The details of vegetation changes to the paleoestuarine plain have been examined using pollen analysis. Studies on the Alligator River systems indicate a remarkably consistent picture of change in pollen diagrams from several cores (Woodroffe et al 1985; Hope et al 1985; Russell-Smith 1985; Grindrod 1988; Clark & Guppy 1988). The big swamp phase, dated at around 6000 years BP is dominated by Rhizophoraceous pollen; there is then a period of transition, and the replacement of mangrove vegetation by freshwater wetlands is recorded in the upper part of the core by the dominance of pollen of grasses and sedges (Poaceae and Cyperaceae), and some species of Myrtaceae, which may be paperbark (Melaleuca), though the family includes many other widespread genera, including Eucalyptus.

This pattern of vegetation change is also indicated on the Mary River in a pollen diagram from drillhole MRH51 from the paleoestuarine plain (Figure 18). Most of the core appears to be dominated by the pollen of Rhizophora which averages 50–60% of the record from 850 cm to 300 cm depth. From 210 cm to 250 cm there is a replacement of Rhizophora by Ceriops/Bruguiera (which cannot be distinguished from each other). These species tend to represent a more landward zone within the mangrove forests (Finlayson & Woodroffe, in press). Sonneratia is present at 230–250 cm, and Avicennia also appears in this transition zone. Above that level mangrove pollen is sparse, the total pollen concentration decreases (much having been lost through oxidation), and Poaceae, Cyperaceae and Myrtaceae increase. This latter phase also includes other pollen types (such as the legume Aeschynomene and the fern Ceratopterus), and grains which were unidentifiable.

While this transition is very similar to that recorded in cores from the Alligator Rivers, the only radiocarbon date which could be obtained from MRH51 is 5780 ± 140 years BP from 730 cm, which is an age which we would expect characteristic of the upper 4–5 m of the core, rather than at the depth it was found. That this transition does occur at the same time as observed in the Alligator Rivers, at least over much of the paleoestuarine plain, is shown in the pollen spectra of cores MRH52 and MRH56 (Figures 19 and 20), which have been radiocarbon-dated 6790 ± 400 and 6490 ± 200 years BP within the big swamp phase, and prior to the transition to freshwater wetland vegetation.
Figure 18  Pollen diagram of drillhole MRH51, paleoestuarine plain
The pollen content of the upper part of MRH49, close to Shady Camp, was also examined (Figure 21), and again the transition from a mixed vegetation with *Rhizophora* at 300 cm, to *Avicennia* at 100–150 cm, and to freshwater vegetation is demonstrated by the increase of Poaceae and Cyperaceae. The lower part of MRH49 is conspicuously laminated with sand and mud lenses. These sediments resemble the laminated channel sands and muds found within the meander tract of the South Alligator River, a facies not identified in meander loops on the Mary River, nor on the similar-sized Adelaide River. Radiocarbon dates at the base of MRH49 of 5470 ± 240 and 5480 ± 180 years BP, also indicate that it has undergone a rather different pattern of development than the usual big swamp transition. These laminated sediments may represent estuarine mouth migration associated with the 5500 year-old shoreline.

### 3.2.2. Coastal plain development

The coastal plain is dominated by bluish-grey muds and muddy fine sands. More than 2 m below the surface these contain variable amounts of shell detritus. Much of the sediment in the upper 2 m is oxidised with some carbonate nodules and jarosite.
Organic fragments are found in the upper 4 m of the drillholes. Coastal history can be reconstructed from radiocarbon dates on wood fragments and shell from drillholes, as well as from pollen spectra from selected cores. The basal transgressive phase was one of landward migrating shoreline around 7000 years ago as sea level rose (Table 5). The shoreline stabilised around 6000 years ago, and this is marked by the landwardmost beach ridge, which is a discontinuous ridge bordering the upland margin and tracing out a broad embayment that reached Shady Camp and Alligator Head. *Anadara* shells at 3.8 m in MRH4, dating at 6650 ± 430 years BP lie close to this most landward shoreline (Figure 22).

**Figure 20** Pollen diagram of drillhole MRH56, paleoestuarine plain
**Figure 21** Pollen diagram of drillhole MRH49, paleoestuarine plain

MRH44 and MRH48 are cores from the coastal plain and their pollen spectra are shown in Figures 23 and 24. Both show a relatively high proportion of mangrove pollen throughout. However, there are subtle differences between these and the cores on the paleoestuarine plain. First, pollen is scarcer than in the classic big swamp sequence, as is indicated by the grain counts. *Rhizophora* is not as dominant within the pollen mixture in the centre of the core as within big swamp sediments. This, taken with the presence of shell through this part of the core, indicates that the sediments were deposited in an open bay environment. Only the base of the cores demonstrates the mangrove-rich, *Rhizophora*-dominated characteristics of mangrove facies, at around 7 m in MRH48 and 8 m in MRH44. This reflects the transgressive mangrove fringe, radiocarbon-dated 7290 ± 160 years BP in MRH48. The period of open bay sedimentation is dated at 5350 ± 210 and 5600 ± 210 years BP, since which time the regressive mangrove fringe has passed over both of these sites.
The upper parts of both cores are oxidised and pollen is hard to recover in the upper 2 m, as shown by the low total pollen grain counts; nevertheless Avicennia is found, with traces of Poaceae. The transition, so typical of the big swamp, is not seen in these coastal plain cores. However, the oxidation history makes it impossible to determine whether the sediments at the top of the cores were deposited beneath mangroves, or whether there are several centimetres of muds deposited beneath freshwater vegetation. Both the pollen and the salinity measurements (total salts in ppm), indicate that the upper part of the coastal plain formed in a more saline environment than the upper floodplain mud unit of the paleoestuarine plain. In view of the observation that very little of the coastal plain is presently above the level of the highest spring tides, it needs to be asked whether mangrove vegetation was replaced by freshwater vegetation because of vertical accretion out of the intertidal zone, or whether, as a result of rapid horizontal buildout, the interior part of the plain became too far from the open water to flood at high tide. Alternatively, the sediments may have compacted since deposition.
The pattern of coastal build-out is dated by radiocarbon ages on shells from depths of 4–6 m in drillholes on the plain. These dates are taken to indicate deposition of shell (some may be in growth position, but this could not be determined during drilling), in a shallow subtidal environment seaward of the shoreline. Drillholes from the western side of the plain support a gradual progradation, with vertical sediment accumulation in a shallowing bay. MRH41 is taken to indicate that the shoreline was landward of that location 5000 years BP, and MRH38 indicates that it was somewhere landward of the present shoreline 3500 years BP and progressively shallowing. Dates from MRH10 and MRH48 are consistent with this because they are both within 2 km of the 6000-year shoreline and therefore represent infill of the embayment around its side at the same time as the progradation. Much harder to understand are the dates on mangrove stumps and associated carbonate nodules of around 5000 years BP found near the mouth of Tommecut Creek. All other evidence points to the shoreline having been landward of this location at this time. The material was sampled in an effort to constrain the age of the paleochannel (see below), but these ages appear unrelated to the paleochannel, which cannot predate the deposition of the plain, and are interpreted to indicate that the coastal plain had built out at this location rather more rapidly than to the west (see 5000-year isochron on Figure 22).

The coastal plain subsequently built out gradually but uniformly until around 3500 years ago when a phase of chenier building commenced. Two anomalous dates from cores in the centre of the coastal plain are difficult to explain. If these are discounted then the pattern of progradation can be reconstructed. Tentative isochrons are shown in Figure 22, together with radiocarbon dates from drillholes across the plains. The plains have accumulated for the most part in a subtidal environment seaward of the shoreline. This is supported by the pollen record from drillholes MRH44 and MRH48 (Figures 23 and 24).

The upper 3–4 m of coastal plain sediments, containing less shell but more abundant organic fragments, record the gradual seaward migration of the mangrove-dominated shoreline. The chronology of chenier ridges is critical to understanding the changes of the last few thousand years. The landwardmost ridge, deposited around 6000 years ago, consists of sand and gravel and is generally deeper than the seaward cheniers, and in many places directly overlies the upland Koolpinyah surface. The younger more seaward features are true chenier ridges, overlying the nearshore muds. The 6000-year ridge represents a rapidly deposited shoreline in a period of abundant mud supply; the chenier ridges on the other hand formed during periods when there was less mud available, and coarse material, particularly shells from the nearshore muds, could be winnowed and concentrated shoreward into a minor shoreline ridge (Chappell & Grindrod 1984).
Figure 23  Pollen diagram of drillhole MRH44, coastal plain
Figure 24 Pollen diagram of drillhole MRH48, coastal plain
3.2.3. Paleochannel activity

Paleochannels are extremely important features on the coastal plain of the Lower Mary River, both in terms of interpreting what has happened in the past, and in trying to predict what will happen in the future. There are three areas in which paleochannels are prominent, firstly along the course of modern Sampan Creek (paleochannels A and B), secondly along the course of Tommycut Creek (paleochannel D), and thirdly to the west of these creeks where a prominent large paleochannel is clearly visible on aerial photographs and satellite imagery (paleochannels C and X). There is also a complex of west-east paleochannels near the coast. These are shown on Figure 25, which also shows radiocarbon dates on material either cored from the paleochannel or exposed in the modern creek banks where these are considered to be incising into the paleochannel. Paleochannels are also present upstream of Shady Camp and it can be inferred that tidal influence extended considerably further inland in the past.

![Diagram of paleochannels and radiocarbon dates](image)

Figure 25  Major paleochannels on the coastal plain, and radiocarbon dates which indicate the chronology of their infill, and on cheniers
Closer examination and mapping of the paleochannels indicates two types of paleochannel, suggesting at least two phases of paleochannel activity in particular locations. There are large tapering estuarine paleochannels such as paleochannel A, which is now partly reoccupied by Sampan Creek, and paleochannel C to the west. Both show a relatively rapid, exponential decrease in width with distance as is typical of major tidal rivers in the area (such as the South Alligator, and Daly rivers; Chappell & Woodroffe 1985; Vertessey 1990).

Reoccupying at least part of the course of these are smaller, less tapering paleochannels such as paleochannel B and paleochannel X (Figure 25). In places these are largely confined within the earlier paleochannel (ie, Roonees Lagoon on Sampan Creek, and much of paleochannel C); elsewhere they strike off on their own. Thus Sampan Creek presently follows the course of paleochannel B south-west of Alligator Lagoon instead of Alligator Lagoon itself which is the course of paleochannel A. Paleochannel D falls into neither of these paleochannel types; its width-distance relationship seems to be intermediate between the two types, partly because the channel is obscured by the creek that now reoccupies it.

A series of questions need to be addressed regarding these paleochannels. First, when were they active and what types of flow did they contain? Second, why did they infill? Third, was more than one paleochannel course active concurrently? Fourth, have flows switched from one paleochannel course to another and if so why? Fifth, how far inland did saltwater penetrate up the paleochannels when they were active? Finally, is the modern pattern of tidal creek expansion directly analogous to past change on the plains and can interpretations of past conditions be used to predict what may happen in the future?

It cannot be determined precisely when a paleochannel was active. However, a channel's age can be constrained by the age of the sedimentary unit into which it is excavated, and by the age of the sediments that infill it. Mangroves may have lined active tidal channels, but there will be no clear discrimination from mangroves infilling the channel, or those growing when the coastal plain was building out. The coastal plain has been built out by gradual coastal progradation, with relatively rapid sedimentation over the period 6000–4000 years BP. The paleochannels cannot therefore have had their present form prior to about 5000 years ago, and those which extend seawards beyond the inland chenier ridge cannot be older than 3500 years.

The chronology of the paleochannels has been established by radiocarbon dating material from within the channel fill. This can only represent a minimum age of the channel, for it marks the infill of the previously active channel. The mangroves which presently line Sampan Creek are producing organic material which is getting incorporated into the sediments, and thus dating of paleochannel infill could yield a date of modern (indeed one date on organic matter marginal to Sampan Creek does yield a modern date, Figure 25). Some paleochannels may have remained open as
billabongs (similar to the discontinuous billabongs upstream of Shady Camp), and infilled long after their initial abandonment as active water courses. It is important to recognise these limitations on dating the paleochannels themselves.

Paleochannel C has been drilled at several sites. Drillhole MRH26 contains muds which are heavily oxidised in the upper 2 m, becoming increasingly sandy, and perhaps laminated, with depth. A wood sample from 9.8 m was radiocarbon-dated 6770 ± 240 years BP. The date appears to record the transgressive rise of sea level across the pre-Holocene basement and not the activity of the paleochannel (Table 5); no material suitable for dating could be extracted from the upper part of this drillhole. However, a series of accelerator mass-spectrometry radiocarbon dates on sediments near the surface from other sites within the paleochannel show remarkable uniformity (Table 4); two dates on fine organics concentrated from muds from paleochannel C, 105–325 cm in MRH60 and 115–165 cm in MRH61, are 3390 ± 100 and 3340 ± 70 years BP respectively. A date on shell from paleochannel X at MRH62 (125–145 cm) of 3640 ± 70 years BP is not directly comparable, because the shells have not been corrected for the environmental-correction (ocean-reservoir effect). As discussed above, this is generally taken as around 450 ± 35 years for shells in the Australian region, but appears to be less, at least for some shells in the van Diemen Gulf region. Paleochannel X must be younger than paleochannel C because it sits within it and partially obscures it; however, these dates imply that it postdates it, or at least that it has been infilled, no more than 100 years later.

A similar argument can be advanced for the eastern paleochannels A and B. Paleochannel B appears more fluviually-dominated, tapering only slightly with distance upstream than paleochannel A. It is narrower, but for part of its course sits within the large, rapidly tapering estuarine paleochannel A. Radiocarbon dates on wood from channel fill provide some indication of the timing of infill after active flow ceased in these paleochannels. The ages for this complex range from 1000 to 2600 years BP. Near the mouth a date on wood from 135 cm in MRH9 gave an age of 1960 ± 200 years BP; it represents only a minimum date. Nevertheless a similar date 1920 ± 190 years BP was determined on wood from a horizontal log found in the bank at the Narrows, where the modern channel appears to be incising into a paleochannel.

At Alligator Lagoon, where a creek is actively cutting into paleochannel A, a paired mangrove stump and a carbonate nodule gave ages of 1000 ± 120 and 1520 ± 70 years BP, respectively. A second stump further along the bank, sampled on a separate occasion gave an age of 1440 ± 180 years BP. These ages suggest that this channel was infilling by 1500 years ago, and that it continued to support mangrove for a period of 400–500 years.

The fluvial paleochannel B is dated at one site where mangrove stumps exposed in the eroding bank gave ages of 1210 ± 110 and 2640 ± 60 years BP (sampled on different occasions). On the basis of these dates both paleochannels A and B appear to have been abandoned and infilling for the last 2000 years.
The form and chronology of paleochannel D, now occupied by Tommecut Creek, is the hardest to decipher. Mangrove stumps initially considered to be in the paleochannel near the mouth, were dated at 5190 ± 80 and 5350 ± 200 years BP, and carbonate nodules at the site of the latter stump were dated at 4990 ± 80 years BP. These are consistent within themselves, but as mentioned above, are considerably older than the age one would normally have ascribed to the coastal plain at this location on the basis of coastal plain dates from elsewhere. A further date on shell, also considered to date paleochannel D, south of this first group of dates, was 4190 ± 80 years BP. On the other hand, there are also younger dates from this paleochannel. A mangrove stump from a site within the paleochannel dissected by the creek now connecting Tommecut and Sampan Creeks yielded an age of 1190 ± 120 years BP, statistically indistinguishable from an age on the adjacent paleochannel B. The two paleochannels cross each other, but they appear to have been infilling contemporaneously. There is also an indication that paleochannel D joins the west-east paleochannel Y, within which mangrove wood from shallow depth has given dates of 890 ± 210 and 390 ± 340 years BP (Table 4).

The interpretation of paleochannel D remains the least satisfactory. The coast appears to have built out more rapidly at this location (the question of whether river supply of sediment is likely to have been the main contributor to coastal progradation is raised below); the oldest dates seem to represent progradation of the coastal plain 5000 years ago, when this course was then the preferred route of the Mary River. This course was probably abandoned in favour of the western course (paleochannel C), and infilled about 4000 years ago. Some subsequent reoccupation of the system seems to have occurred, perhaps only as a secondary route taking overflow from paleochannels A and B, as they became infilled after 2000 years ago. All three paleochannel courses (A, B & D) were infilling, with fringing mangroves, 1500 to 1000 years ago, and the west-east paleochannel Y has infilled since that time, perhaps as part of the same infilling process as paleochannel D, which started upstream and took more than 1000 years for completion.

Some answers can be offered to the questions posed above. There appear to have been two large macrotidal estuarine mouths (similar in form and process to the modern South or East Alligator mouths), these being paleochannel C which was active around 4000–3500 years ago, and paleochannel A which was active around 2500–2000 years ago. These were tidally dominated and were not active concurrently. Each was infilled, initially rapidly, but with gradual billabong scouring and refilling persisting, in some cases up to the present day. Whatever the cause of abandonment (see discussion below), the fluvial flow of the Mary River required that some course remain open to the sea, and a fluvial channel can be identified that became active during the infill of the former estuarine channel. In the case of paleochannel C, paleochannel X operated during the abandonment of the large estuarine course, and in the case of paleochannel A, paleochannel B operated, and for a time paleochannel D may also have taken some of the flow. These fluvial paleochannels were not active for long. Infill of the western course was fairly
complete 3000 years ago. By and large these alternative paleochannels do not appear to have been active concurrently, the most probable exception being Tommeycut Creek (paleochannel D) which may have taken some of the flow from paleochannel B, as it does at present. It is not clear how paleochannel A was excavated on the abandonment of paleochannel X.

The Mary River at Shady Camp lies within a paleochannel (labelled paleochannel H on Figure 25). There are at least three other paleochannel courses which pass through the constriction between Alligator Head and Shady Camp (F, G1 and G2 in Figure 25). Paleochannel C may have been fed by paleochannel F, the westernmost course through the constriction. In Wet season floods, some flow presumably follows each of these depressions, as was shown for gaugings undertaken in 1957 and in 1993.

3.3. Interpreting the Holocene changes

The geomorphology of the Mary River plains is summarised in Figure 17 for a schematic longitudinal profile along the axis of the river. Beneath the estuarine and coastal plain muds, and overlying pre-Holocene sediments, there are transgressive mangrove muds representing a shoreline that has migrated inland as the sea rose in response to postglacial ice-melt of polar and high latitude ice sheets. The paleoestuarine plain was rapidly infilled with vertically accreted muds, beneath extensive mangrove forests that existed south of Shady Camp around 6000–5000 years BP.

A schematic diagram of the Holocene evolution of the Lower Mary River plains over the last 7000 years is presented in Figure 26. The area was first inundated as sea level rose, such that by 7000 years ago there was a relatively widespread mangrove forest in the floor of the prior valley. It encroached rapidly landwards as sea level rose, and mangroves would have progressively replaced the open eucalypt woodland that occupied the prior valley. This transgression terminated around 6000 years ago, during the big swamp phase (Figure 26b). At that time most of the area south of Shady Camp and Alligator Head was occupied by Rhizophora-dominated mangrove forest, and the shoreline was a smooth sandy shoreline indicated by the landward beach ridge. Quite what form the mouth of the river took is unclear, but the laminated sediments, marking post-5500 year deposition in MRH49, suggest that it may have been a relatively open mouth through the constriction between the two heads.

Mangrove persisted south of these heads 5000 years ago, but rapid progradation of the coastal plain was under way (Figure 26c). As indicated above, dates from near the mouth of Tommeycut Creek suggest more rapid build-out there than elsewhere on the plain, though details are elusive; perhaps there were a series of mangrove covered islands within the bay which became incorporated within the plains as they prograded. By 4000 years ago, the coastal plain had built out until it was at or close to the landwardmost of the sub-parallel chenier ridges. The Mary River flow was concentrated within the western paleochannel (paleochannel C), a course which must have been occupied by avulsion, perhaps because it offered a shorter course to the
Figure 26 Schematic diagram of the Holocene evolution of the Mary River plains

can, if the 5000-year shoreline shown in Figure 26c is correct. The landwardmost chenier is found to the west of that paleochannel, but not on the plains to the east, and longshore drift of sediment from the west may explain the morphology of this chenier
ridge, and explain why the channel veered to the east before exiting into the gulf. By 4000 years ago, mangrove had disappeared from most of the paleoestuarine plain, but the date of 3920 ± 270 years BP in MRH12 suggests some localised mangrove persistence, and supports the contention that mangrove did extend south of Shady Camp when the large estuarine paleochannels were occupied. The freshwater wetlands may have appeared as early as 4000 years ago (the date favoured by Woodroffe et al 1986 for their appearance on the plains of the South Alligator); though given that it is difficult to date the upper part of the pollen transition, the replacement could have occurred in the last 2000 years as favoured by Hope et al (1985) and Clark & Guppy (1988) elsewhere in the Alligator Rivers Region. Mangrove is likely to have persisted on the coastal plain for much longer and it seems likely that freshwater wetland would have replaced mangrove first at the southern end of the paleoestuarine plain, adjacent to the alluvial plain, as a wedge of floodplain mud formed over the mangrove facies. Such freshwater clays are thinnest, if they exist at all, over the coastal plain, and indicate the latest replacement of mangrove nearest the coast.

By 3000 years BP the western paleochannel had been abandoned and was largely infilled. In its final stages of infill, a fluvially-dominated channel (paleochannel X, perhaps maintained only by river flood discharge) took the flow of the Mary River to the coast, occupying a portion of the former channel, but both had been infilled by 3300 years ago, and may have been a series of linear billabongs not much different from the ones presently occupying them. The Mary River emptied into the gulf through the eastern estuarine paleochannel (paleochannel A), which again was a large tidally-dominated channel (like the present South Alligator). At this time the coast was in a position not far short of its present position, and the dates on cheniers, and the form of those to the east of the plains, suggest that these cheniers flanked the shoreline, and recurved into the mouth of the estuary. The status of the mouth of Tommycut is uncertain, but chenier ridges along that part of the coast appear to have been under little or no influence from any river mouth at that point (Figure 26e). The eastern paleochannel was abandoned after 3000 years ago, and before 2000 years ago, by which time the paleochannels were infilling (including paleochannels A, B and D, the latter two of which appear to have been short-term fluvial conduits to the sea active in the final stages of abandonment of the estuarine channel).

The last 2000 years appear to have been a time of minimal change on the plains. The freshwater wetlands were established on the paleoestuarine plain, and over much of the coastal plain. There seems to have been no major outlet of the Mary River, and certainly no major tidal outlet of the dimensions of the former channels C and A. Paleochannels D and Y were progressively infilled from landward to seaward. Chenier ridges formed on the coast, but there was no major progradation, the most marked advance having been in the very east of the area, in front of Point Stuart (Clarke et al 1979; Lees 1987).
3.3.1. Sediment provenance

It is apparent from Figure 17 that there are large volumes of sediment within the plains and that much of this was deposited 7000–6000 years ago. The provenance or source of this sediment is not clear. The Mary River does not presently carry a large mud load from its catchment. Indeed calculating from denudation rates, such as those determined for the Adelaide River catchment, the total annual sediment input into the river system would be around 2–4 x 10^4 t/yr (Williams 1973). Using rates for the smaller Magela Creek catchment, and basing the estimate on washload and solute load considered to be derived from surface lowering of the low-lying Koolpinyah land surface at a rate of 28 m^3/km^2/yr (Roberts 1991), the annual sediment load would be around 5 x 10^5 t/yr. These rates of supply are nearly an order of magnitude less than would be necessary to fill the prior valley to the extent that it has been infilled in the last 7000 years, taking sediment bulk density into account. The discrepancy between rate of sediment accumulation and fluvial sediment supply could be explained by one of three hypotheses: i) the sparse gauging data significantly underestimate the rate of suspended sediment transport downstream; ii) the rate of sediment supply has changed since the mid-Holocene; or iii) there has been an alternative source of fine-grained sediments. These are examined in turn below; the third hypothesis is favoured and it is suggested that much of the sediment has come from seaward, moved by rapid tidally-driven currents, during the transgressive phase.

There have been relatively few detailed gaugings to allow calculation of sediment budgets down the rivers of the Top End, and there is certainly a large error term associated with extrapolation of the few observations to calculate rates over the Holocene. Nevertheless, Figure 17 indicates that the rate of sediment retention within the plains has decreased during successive millenia from rates of around 10 x 10^6 t/yr 7000–6000 years BP to negligible sediment retention over the last 2000 years.

At the time of the last glacial maximum, around 20 000 years BP, conditions in northern Australia were much drier than now (Webster & Streeten 1978). Vegetation-derived climate reconstruction from the Atherton Tablelands lends support to the idea that mid-Holocene conditions were temporarily wetter than now (Kershaw 1983). It is possible that wetter conditions allowed more sediment to be moved down the rivers; however, present suspended loads would need to have increased by about an order of magnitude to explain the sediment stored within the paleoestuarine plain. The catchment contains Quaternary alluvium that may have been eroded under wetter conditions, but it is not a catchment which is presently supplying large volumes of fine-grained material. Landscape denudation in the region is weathering limited, as much as transport limited, and it is highly unlikely that such enormous volumes of sediment could have been mobilised from the catchments in such a short period of time.

Some recent interpretations have invoked a wetter period in the monsoonal tropics of Australia in mid-Holocene (Lees & Clements 1987; Lees 1992; Shulmeister 1992). However, these studies are based upon dating of cheniers, and the sediment stored
within the plains is presumed fluvial in origin (Rhodes 1982). These authors used the Point Stuart site in their interpretation; extending their logic to the Mary River plains would require an extremely wet period to account for the sediment volume of the entire coastal plain between the 6000-year shoreline, and the landwardmost 3500–3000 year cheniers.

All river and stream systems along the southern shore of van Diemen Gulf have extensive deltaic-estuarine plains which formed around 6000 years ago, and whose area seems unrelated to catchment size (Figure 1). The area of coastal plain, developed during the last 6000 years, varies considerably, with extensive areas in the west, and smaller coastal plains in the east (Table 1), irrespective of catchment size. It has been suggested elsewhere (Woodroffe et al 1993) that the major sediment supply has been from seaward (almost all the sediment has, of course, been derived from the land in the first place, but may have undergone various periods of storage offshore).

A seaward sediment source is partly supported for the South Alligator River by marine foraminifera assemblages in cores from the estuarine plains. Rapid tidal currents and flow asymmetry may have helped to move sediment upstream, perhaps also enhanced by Dry season evaporation of water from the channel and plains (Chappell 1990). Progradation of the coastal plain, although punctuated by the formation of sandy ridges around 6000 years ago, and since 3500 years BP, was more-or-less contemporaneous along the southern shore of van Diemen Gulf. Most rapid build-out was around 5000 years ago, and there has been relatively little net advance since 3000 years ago. Instead coastal sedimentation has been interrupted by the emplacement of small sandy and shelly cheniers. The reason for the deceleration of coastal progradation is not altogether clear; there seems little evidence that this is a deeper part of the gulf and that more sediment is required for the same planimetric advance and that it is therefore a reflection of embayment geometry (Chappell & Grindrod 1984). Perhaps the seaward sediment source within wave base has been exhausted as has been suggested for offshore sand deposits on the New South Wales coast (Roy et al 1980; Roy 1984).

3.3.2. Channel switching

The possible existence of a regional climatic control on the occupation and abandonment of paleochannels needs further consideration. The evidence for Holocene climatic change in the Top End is poor and ambiguous, as discussed above. Nevertheless, there appears to have been some synchroneity in phases of paleochannel occupation and abandonment between adjacent river systems. On the South Alligator, paleochannels have been dated at around 4000 years BP with a younger period of infill 2600–1300 years BP (Woodroffe et al 1986). These paleochannels are broadly similar in age to those on the Mary plains, but they have undergone different processes of formation and infill. Paleochannels on the South Alligator River are typically ox-bow cutoffs which have resulted from channel meandering and lateral migration, and subsequently infilled with sediment from suspension. On the Adelaide River, a prominent paleochannel on the eastern plains has been dated as infilling 2300
years ago, also corresponding to the later phase of infill on the Mary River (Woodroffe et al 1993). Despite similarities in timing, there are other systems with much more extensive phases of meandering and cutoff (ie, the Daly, Chappell 1993), for which the dating of paleochannel infill is relatively imprecise. There is presently insufficient evidence to support regional phases of paleochannel activity.

Several hypotheses for the abandonment of Mary River paleochannels can be considered: either i) the active course may have been dammed at the mouth, perhaps by events associated with chenier formation; or ii) there may have been a slight fall of sea level so the channels were no longer tidal and filled in fluvially; or iii) fluvial flow may have been diverted and former estuaries may have infilled with tidal sediment.

While the chenier ridges appear relatively continuous across the seaward face of paleochannel C, such small ridges, presently with minimal surface expression, could not have dammed such a large estuary. It is important to note that the Adelaide River, which is a very similar size in terms of catchment area to the Mary, also has a blocked paleochannel on its eastern margin, and the radiocarbon age of sediments within that paleochannel indicates that it was infilling before 2000 years ago, roughly contemporaneously with paleochannel A on the Mary plains (Woodroffe et al 1993). Smaller rivers such as the Wildman and West Alligator, though they contain similar chenier sequences, have not been dammed.

The pattern of sea level change during the last few thousand years is more clearly recorded for Queensland, where it has fallen by less than 1 m in the last 3000 years relative to all sites studied around northern Queensland, with exact change varying with isostatic adjustment (Chappell et al 1982). Evidence from the South Alligator plains is summarised by Woodroffe et al (1987, 1989), but is relatively imprecise during the last few thousand years, as a result of the large tidal range. Nevertheless any substantial fall of sea level at this time is contrary to almost all sea level studies from the Australian region, and minor shifts would be unlikely to affect the tidal prism sufficiently to lead to abandonment of the estuary. Some estuaries, such as the Gilbert River estuary in the Gulf of Carpentaria, do, however, have shoaled mouths that close at low tide (Jones et al 1993).

The third alternative is that the fluvial flow was diverted, and that the former estuary then filled in by tidal processes. The chronology suggested above is that the channel occupied by Tommecut Creek (paleochannel D) is the oldest; that flow then switched to the western paleochannel (paleochannel C), and when this was abandoned switched to the eastern paleochannel (paleochannel A). Paleochannel C would have represented a shorter course to the sea around 5000 years ago, if the interpretation of the pattern of coastal buildout (Figure 22) is correct. Paleochannel A may have offered a shorter course to the sea than the sinuous paleochannels C or X, as these were diverted eastwards by longshore drift and chenier formation. However, for the last 2000 years we cannot identify a major fluvial outlet into the gulf, and while minor creeks may have served as overflows for freshwater floods which accumulated on the plains, the bulk of the freshwater must have evaporated from the plains during that
period. Thus the switching of channels may have been determined by fluvial diversion, but fluvial diversion is not regarded as the trigger for infill.

Paleochannel C infilled before it was reoccupied by paleochannel X, and all of this happened within the space of 100 years or less (based on the radiocarbon dates). A mechanism needs to be identified by which an estuarine channel can rapidly infill. Generally in geomorphology the feedback mechanisms which operate are negative feedbacks, which tend to discourage rapid change, and maintain systems in quasi-equilibrium states. It is hypothesised here that the infill of these tidal estuaries may have been an example of a positive feedback.

On the South Alligator River tidal flows are asymmetrical, with the flood tidal velocities exceeding the ebb tidal velocities, and with tidal asymmetry becoming more pronounced further upstream. This promotes the movement of sediment upstream, particularly the further upstream in the system one goes (Woodroffe et al. 1986). In that river, and the neighbouring East Alligator, Wet season fluvial flows are large enough to move sediment downstream again in the Wet season, keeping the system clear. Nevertheless the upstream movement of sediment has served to concentrate sediment in the middle reaches of the river, and is probably the explanation for why both the South Alligator and East Alligator Rivers have cuspatate meandering segments in their middle reaches (Woodroffe et al. 1986). The South Alligator, at least, has become wider and shallower in the last 2500 years, than it was in previous meandering courses (Chappell et al. 1993).

It is postulated here that this tendency for macrotidal estuaries to infill with sediment might infill channels where the catchment is not large enough to reopen the channel during Wet season floods, or at least retard outflow of Wet season sediment loads. The Adelaide River and the Mary River are of similar size catchment, and their paleochannels appear to have infilled at around the same time. Kingston (1991) has observed that the Wildman and West Alligator Rivers are shoaling in their tidal reaches, and there is a seasonal shoal across the mouth of the mesotidal Gilbert River in the Gulf of Carpentaria (Jones et al. 1993). Large rivers such as the Daly River, are easily maintained by their considerable freshwater flood flows, but have very active channel migration across their floodplains (Chappell 1993). Neither the Adelaide or Mary Rivers shows evidence that it has been actively migrating by lateral migration across its plains. Indeed the similar elevation of levées inside and outside meanders, and in straight stretches (see discussion above) indicates that the estuarine channel remained relatively immobile within its course.

It is thus hypothesised that the estuarine channels of the Mary River infilled through a positive feedback, wherein concentration of sediment from seaward into and upstream in the estuary increased the tidal asymmetry and hence the ability to concentrate further sediment upstream, infilling the estuarine channel, and confining the fluvial flow to a course, partly within the former estuarine channel, which was particularly prone to avulsion (as occurred from paleochannel X to paleochannel A), or total occlusion as seems to have occurred around 2000 years ago.
3.4. Summary

1. The broad pattern of Holocene sea level rise and sedimentation on the Lower Mary River plains resembles that of the South Alligator plains, where a model for the geomorphological development of the tidal river and plains has been proposed (Woodroffe et al 1986, 1987). Three major phases are identified on the South Alligator: a transgressive phase (prior to 6800 years BP); a big swamp phase (6800–5300 years BP); and a sinuous/cuspate phase (since 5300 years BP).

2. The plains of the Mary River are underlain by bluish-grey mud, which are Holocene in age and derived from seaward sediment sources. Various analyses such as sediment size, total salts, pollen analyses, and radiometric dating, assist in determining the depositional environment under which the various parts of the plains formed.

3. A basal mangrove facies overlies the pre-Holocene surface of the coastal and paleoestuarine plain and represents the mangrove shoreline that existed under the marine transgression, about 7000 years ago. As sea level stabilised mangrove forests established giving rise to a big swamp phase in the paleoestuarine plain. Sedimentation on the paleoestuarine plain continued at a decelerating rate, through vertical accretion under the mangrove forests, until about 4000 years BP when freshwater floodplain clays were deposited and freshwater wetlands replaced the mangrove forests.

4. A discontinuous ridge, forming a broad embayment that extends inland as far as Shady Camp and Alligator Head, marks the position at which the shoreline stabilised 6000 years BP. The coastal plain build out by gradual progradation with relatively rapid sedimentation over the period between 6000–4000 years BP. A further phase of chenier building commenced around 3500 and the shoreline reached its present position about 2000 years BP and has changed little since.

5. The paleochannels on the coastal plain have a maximum age of about 5000 years and those which extend seaward of the inland chenier ridge are younger than 3500. At least two types of paleochannel can be identified: large tapering estuarine paleochannels and smaller, less tapering and more fluvially-dominated paleochannels. Two large macrotidal estuarine mouths were active at different periods in the past, similar to modern adjacent tidal rivers. Each was abandoned and fluvial paleochannels became active during the infill of the former estuarine channel. These alternative paleochannels do not appear to have been active concurrently.
4. RECENT CHANGES TO THE LOWER MARY RIVER PLAINS

It is apparent from the last chapter that the plains of the Lower Mary River have changed markedly over the Holocene. A series of very rapid and far-reaching changes are presently occurring on the plains. Aerial photographs enable the reconstruction of these changes over the last 50 years. These recent changes, particularly the pattern of saltwater intrusion, are examined in some detail in this chapter and the extent to which the recent changes are part of the natural dynamics of the plains is assessed.

4.1. Recent coastal change

Considerable changes in the position and nature of the shoreline can be detected from aerial photographs over the last 50 years (Figure 27). Erosion has dominated to the west of both Tommcut and Sampan Creeks, with coastal retreat of up to 400 m to the west of Tommcut Creek (Figure 28). Accretion has occurred to the east of Tommcut Creek.

![Diagram showing changes in coastal area from 1943 to 1989.](image)

**Figure 27** Detail of coastal change 1943–1989
Retraction of the mangrove fringe is indicated by a zone of dead *Avicennia* landward of the coastal mangrove fringe, and by mangrove stumps across the mudflat seaward of the fringe (see Plate 5). The landward presence of dead *Avicennia* is consistent with a successional trend, such as might accompany gradual build-out of the mangrove fringe, while the destruction of mangroves, indicated by mangrove stumps, suggests an interruption in this pattern, possibly as a result of storm-related coastal retreat.

In addition to changes in the coastline itself, the aerial photographs indicate an increase in the area of saline mudflat and loss of upper coastal plain, as saltwater has caused dieback of sedges and grasses. The overall area of mangroves has not altered greatly but has changed in distribution, reflecting the changing patterns of erosion, accretion, and saltwater intrusion.
4.2. Recent expansion of the tidal creek network

A dramatic expansion of both Sampan and Tommecut tidal creek systems has also occurred since the late 1930s to early 1940s. Both systems have formed a rapidly extending dendritic network of creeks invading freshwater wetlands and causing dieback of large areas of Melaleuca (Plate 9). The pattern of extension has been mapped in detail from aerial photographs (Knighton et al 1991). Mapping has been standardised for scale of photography, as described by Knighton et al (1992). Figure 29 shows the reconstruction of the networks from photography for the years 1943, 1950, 1963, 1973, 1980 and 1989. The creek system, as mapped from 1991 aerial photography, is shown on Figure 30, indicating the extensions and contractions from the 1989 network.

Plate 9 Tidal creek extending into inland saline basin with associated paperbark (Melaleuca spp.) dieback

It is important to recognise that the dendritic creek system, shown in Figures 29 and 30, and examined in greater detail in Figures 31, 32 and 33, is not the only route for saltwater incursion to the plains, but instead represents a clearly defined channel system regularly flushed by the highest tides.
Figure 29 Expansion of Sampan and Tommucut Creeks, 1943–1989
(Knighton et al 1992)
Figure 30 The tidal network mapped from 1991 aerial photography, and comparison with the network mapped from 1989 aerial photography.
Saltwater can also flow across the plains as sheet flow. Such diffuse flows have preceded the excavation of creeks in many instances, and mean that the extent of saltwater influence may have been more extensive in a particular year than shown by the dendritic system mapped in Figure 29. For example, the extent of saltwater influence in the 1950s went beyond Sampan and Tommucut Creeks, as is shown by maps prepared by staff of the Water Resources Division.

Figure 31  Expansion of tidal creeks on the western side of Tommucut Creek, 1950–1989 (from Woodroffe et al 1991)
A detailed study of the plains was undertaken in 1957 (Kutena 1957) at which time aerial surveys were undertaken. Dead Fish Billabong on Tommucut Creek and Roonees Lagoon on Sampan Creek were mapped as tidal on the 1958 update of that 1957 mapping, though tidal flows are not recorded on the flood hydrograph in Roonees, except perhaps as elevated water levels at the highest spring tide, before the gauge was discontinued in 1964. It was noted that in December 1957 much of the plains were dry, including vast areas of paperbark swamps and that 'to the north the coastal belt was practically dry excepting in Tommucut Creek and Sampan Creek where some local flooding due to the tide was present' (Watts memo, 16/12/57). However, December 1957 was an extremely dry start to the Wet season, with water level records at the Mount Bundey Station much lower than in subsequent years.

Not only were there cases of saltwater penetration beyond the creek system, but there were also instances where there was a connection between tidal creeks and predominantly freshwater billabongs on the plains. For instance, on 1943 photography there appears to have been a connection between the tidal creek immediately west of Tommucut Creek, and the linear billabong occupying paleochannel C.
Figure 33 Expansion of tidal creeks into Alligator Lagoon, 1973–1989 (from Knighton et al. 1992)
This connection was presumably a conduit for freshwater retained within the perennial wetlands of the paleochannel system. Other similar connections between predominantly freshwater billabongs and the tidal creek system also appear to have existed. These apparently did not carry saltwater into, or far up, the freshwater systems, because they were small tidal creeks. Distinguishing whether water remaining on the floodplains was saline or fresh, has been difficult if not impossible from the aerial photographs and hampers mapping the extent of salt-affected areas from year to year; a problem that is also experienced with the use of satellite imagery (Jolly & Chin 1992).

Detailed analysis of the tidal creek system, particularly by Knighton et al. (1992), reveals that the topological properties of the creek networks closely resemble those of river systems, and that they evolved in a regular, rather than a haphazard, fashion. The adherence of this tidal creek network to the series of empirical relationships observed for river systems, known as Horton's laws (Horton 1945), suggests that the creeks have evolved in a regular way, rather than as a response to some erratic external factors, such as buffalo swim-channel excavation. There are numerous distinct linear channels across parts of the Mary River plains, which can be attributed to Wet season buffalo activity and which are mapped as swim channels on the accompanying geomorphological map. Only in certain instances have swim channels become occupied by tidally active creeks. Swim channels are typically linked to areas of dry ground, such as bedrock outcrops or chenier ridges; some examples of such swim channels can be seen in Figure 34. Swim channels may also cross low-lying linear wetland areas, such as paleochannels and paleocreeks, at right angles. This can be seen on the Mary River plains, but is especially evident on heavily degraded parts of the South Alligator system. Where such swim channels have been incorporated into the expanding network they are usually distinguished by right-angled junctions to a more major creek. Thus, for instance, the creek which connects the upstream end of Tommyncut Creek with Sampan Creek has the linear characteristics of a swim channel, and this may explain why the connecting creek does not follow the paleochannel all the way to the previous junction with Sampan Creek.

The topological characteristics of the tidal creek networks have been examined by assigning a 'magnitude' to each link in the network of creeks (Knighton et al. 1991, 1992). Headwater creeks, the smallest creek size clearly definable from the aerial photographs (typically at a scale of 1:50 000), are assigned a magnitude of 1. Magnitudes for tributaries are summed at each confluence, so that the mainstream is assigned a magnitude equivalent to the number of headwater creeks draining into it or its tributaries. Magnitude thus serves as some functional measure of the size of a network.

The evolution of the network can be depicted by the increase in the magnitude of the network over time. By 1989, Tommyncut Creek had expanded exponentially to a magnitude of 829 and Sampan Creek to a magnitude of 590. Mapping of these creek
systems from the 1991 colour infrared photography (Figure 30) again indicates that they had generally continued to increase in magnitude and that Tommecut Creek had a magnitude 872 and Sampan Creek 678 (Figure 25).

It has been suggested that network evolution could be subdivided into various phases, though individual creek networks might not necessarily progress through all phases sequentially (Woodroffe et al 1990, 1991; Knighton et al 1992): i) initiation; ii) extension by headward growth (elongation) and tributary addition (elaboration);
iii) maximum extension; and iv) integration through abstraction and capture. The relative balance of elongation and elaboration is strongly influenced by the relation of individual networks to paleochannels.

Growth of a particular network appears to be inhibited either when the creek system reaches a microtopographic divide, or when it reaches a particular drainage density. This has tended to be experienced first in the more established, downstream parts of the network. In comparing the pattern of network magnitude increase in increments of distance from the mouth, striking parallels between Tommcut and Sampan Creeks are apparent, and the character of network growth appears to vary in an upstream progression (Knighton et al 1992). Near the mouth, tributary creeks appeared to have reached a stage of arrested development by 1989; in the middle reaches, 4–8 km from the coast, linear or weakly exponential growth was discernible; whereas in the headwaters of the main creeks, growth was strongly exponential.

Knighton et al (1992) suggested a model whereby network evolution was viewed as a wave of dissection moving progressively upstream as base level was lowered. This model might allow some predictive insight into future trends in creek magnitude on the plains. Analysis of 1991 aerial photography permits some refinement of that model (Figure 35). Comparison with 1989 photography suggests that new creeks have been excavated or extended, in addition to the occurrence of some abstraction or loss of creeks.

![Graphs of Tommcut and Sampan Creeks](image)

**Figure 35** Exponential increase in network magnitude through time, Sampan and Tommcut Creeks, 1943–1991 (modified from Knighton et al 1992)
The trends in magnitude are plotted in Figure 35; Sampan and Tommymcut Creeks have continued to show parallel development, but some modification to the interpretation of the pattern of evolution seems warranted, based upon extension or abstraction with distance from the mouth (Figure 36). In the downstream section, 0–4 km from the coast, there has been little change in the magnitude of the tributary network, reflecting relative stability of the system. Those tributaries at 4–6 km from the mouth no longer appear to be rapidly extending. However, between 6 and 8 km from the mouth, rapid exponential growth of the network is still continuing. Tommymcut Creek is showing rapid extension at 12–14 km and in its upstream 16–22 km (Plate 10). Sampan Creek, on the other hand, does not appear to be extending from 8–16 km, but is undergoing rapid extension upstream of 16 km from the mouth.

The wave of dissection, which Knighton et al (1992) suggested has progressed upstream, as the main channels deepened, giving a greater head of water entering tributaries in the more upstream part of the system, has altered in character as it progressed upstream. The time from initial dissection to stability and even abstraction has been shorter in upstream segments than in those nearer the mouth. This may be related to hydrodynamic modification of flow characteristics at greater distances upstream.
Figure 36 Changes in network magnitude through time for tributary networks at given distances from the mouth of Sampan and Tommycut Creeks, 1943–1991 (modified from Knighton et al 1992)
Figure 30 indicates some regularity to the distribution of extension and abstraction in the network over the last few years (1989–1991). Additions to the network have largely been in the form of elongation of existing creeks (rather than elaboration of the network), whereas abstractions have more often been from within the network, representing a simplification of the network. Where headwater creeks have become smaller this has tended to be in areas of high drainage density (such as between Sampan and Tommycut Creeks in the 4–12 km segments from the mouth), or where the system has connected up and the creek network has been captured.

Figure 37 shows a series of cross-sections of tidal creeks; there is a relatively consistent relationship between creek cross-sectional morphology and location in the network. Cross-sections in the headward tributaries are initially shallow, broad seepage zones, with an extensive wetted perimeter. Once the muds have been wetted, and the clays lose their cohesiveness, incision can occur, and creek depth increases rapidly, so that the creek changes from a high width-depth ratio to a low width-depth ratio. Deepening occurs rapidly in creeks of low order and low magnitude, but cross-sectional area then increases as the tidal prism gets larger. Narrow, but incised creeks, can be seen in the cross-sections of Alligator Lagoon (Figure 37: SCP1, SCP2, SCP3, SCP4 and SCP6), and in other tributary creeks (Figure 37: CP11 and CP12), and contrast with those of the main Sampan Creek channel (Figure 37: SCM04, SCM05, SCM15 and SCM14).

Overall the expansion of the system has represented a considerable removal of sediment from the plains. The volume of the creek network has been calculated by determining the average cross-sectional area for creeks of particular order (Figure 38), and multiplying this by the total length of creek of that order. The present network (1989) is calculated on that basis to have a volume of about $7.7 \times 10^6$ m$^3$. Using the same cross-sectional area to order relationship and network length for previous years, the exponential growth in the volume of the network can also be shown (Figure 38).

While the net movement of sediment has been out of the mouth of Sampan and Tommycut Creeks, there has also been some infilling of previous billabongs within the network. Thus, for instance, the long, freshwater billabong known as Sampan Billabong between the Narrows and the S-bends on Sampan Creek used to be a broad, open water body. This has filled in with sediment during the evolution of the network, in order to be closer to the morphological equilibrium required by the evolving tidal hydrodynamics (Plate 11). This accounts for the wide, but shallow cross-section of Sampan Creek at this point (Figure 37: SCM02 and SCM01), and for the largely unvegetated banks, except for the presence of salt-tolerant grasses and more recent colonisation by mangroves.

Since Sampan Creek has rejoined with Shady Camp, the Mary River's fluvial discharge (or that which gets over the Barrage) can discharge directly to the sea. The results of a gauging exercise, carried out during a year when only a small Wet season flow overtopped the Barrage, are discussed below.
Figure 37 Cross-sections of creeks at different points over the network. Surveys undertaken largely by Land Conservation Unit, CCNT.
Figure 38 The relationship between estimated volume of sediment eroded from the plains by creek networks and time, and between cross-sectional area and creek order.

Plate 11 Infill of Sampan Billabong resulting in deposition of mud banks; *Mimosa pigra* in background.
Sampan Creek appears to be evolving into a channel which has characteristics more typical of a fluvial palaeochannel than of other headward tributaries. Fluvial palaeochannels tend to have a fairly characteristic width (see palaeochannel B and X, Figure 25), similar to the width of Shady Camp Billabong and other freshwater billabongs of the palaeoestuarine plain. The implications of this for the future evolution of the network are examined below.

4.3. Possible causes of the recent changes

The previous section described the nature of recent tidal creek development on the Lower Mary River plains. Saltwater intrusion has resulted from the gradual extension of tidal influences along prior and existing channels (Plate 12), the expansion of small tidal channels and the formation of new channels into freshwater areas. The changes caused by this intrusion include the destruction of freshwater communities in swamps and billabongs; subsequent filling of billabongs with tidal sediments; dieback of Melaleuca stands; and tidal flooding and accretion of sediment on floodplains adjacent to and at the end of tidal channels (Finlayson et al 1988). The extent of the saltwater intrusion problem on the Mary River can be appreciated by the fact that over 17 000 ha of the total area of floodplain and wetland, estimated at 90 000 ha, has been destroyed by saltwater intrusion, including 6000 hectares of Melaleuca (see Plates 2 and 9) and a further 35–40% are immediately threatened (Applegate 1990).

Plate 12 Mangrove fringed tidal creeks occupying a large palaeochannel meander
No single reason for the recent phenomenon of saltwater intrusion can be readily identified but a combination of several factors, some interrelated, may have tipped the balance reverting the system from a predominantly freshwater wetland environment to one dominated by saltwater conditions. The Lower Mary River plains are particularly prone to saltwater intrusion because of a combination of the large tidal range, the small elevational differences across the plains (much of the lower coastal plain is below the height of the highest tide, Plate 13), and the existence and distribution of vulnerable paleochannels. Billabongs, representing incompletely infilled paleochannels, allowed rapid saline intrusion through existing watercourses when these were initially intruded by saltwater (ie, Sampan and Dead Fish Billabongs). However, tidal creek extension has occurred not only on the Mary River, but to a lesser, but varying, extent also on other tidal rivers in the region (Fogarty 1982).

The evidence for each of six possible explanations is reviewed below: sea level change; rainfall variability; direct human effects; buffalo impact; consolidation and compaction of the plains; and a natural cycle of change.

Plate 13 Saline mudflat under high tide conditions, with chenier ridge in the foreground above the level of inundation and the coastal mangrove fringe in the background
4.3.1. Sea level change

Salinisation might be due to a change in sea level. Although this has not been widely claimed as a cause of the recent saline intrusion, it deserves further discussion in view of projected global warming and associated sea level rise. Analyses of the Darwin tide record have provided different conclusions. Aubrey and Emery (1986) detected a slight falling trend, (0.4 mm/year between 1957 and 1976), whereas the National Tidal Facility (Flinders) indicates a slight rise in sea level (0.28 mm/year) over a slightly longer period. Bryant et al (1988) suggested that the falling sea level trend derived for Darwin by Aubrey and Emery (1986) is likely to be an artefact of the short length of the record and a reflection of more frequent ENSO events and decreasing trade winds in recent years. The suggested trends are at least an order of magnitude less than the tidal measurement errors ± 10 mm (D Williams, pers. comm., 1992). Any net change of sea level appears to have been negligible (Woodroffe et al 1991), and insufficient to explain the dramatic, and ongoing change on the Mary River plains. Nevertheless, although a previous rise in mean sea level does not appear to be the cause of recent rapid tidal creek extension, the pattern of extension may indicate a response that this low-lying coastal freshwater wetland could show to any future sea level rise, such as that considered likely to result from global warming (see section on the implications of future sea level rise).

It is possible that a temporary elevation in water level related to a single, isolated storm event or surge, could have occurred. The height/recurrence interval curve for Darwin, constructed by Hopley and Harvey (1979), indicates that surges exceeding highest spring tide level by 0.5 m or more are likely to occur every 100–150 years, on average. However, the Wet season storm surge effect caused by the coincidence of low pressure atmospheric systems, prolonged landward winds, wind-generated currents and high water discharges from rivers (Stark 1978) is particularly pronounced in shallow semi-enclosed basins such as van Diemen Gulf. The combination of a storm surge and high spring tides could, therefore, result in significant temporary increases in tidal elevation, certainly well within the range required to breach the Chambers Bay coastline.

The Bureau of Meteorology calculated an average decadal incidence of 6.6 tropical cyclones in the van Diemen Gulf region between 1909 and 1980. Two severe cyclones are described for the Mary River region by Murphy (1984) at roughly the time of the creek initiation. The March 1937 cyclone had winds gusting to 158 km/hr and damaged the city of Darwin, whereas the March 1940 one gusted to 106 km/hr, but occurred shortly after severe flooding. Although it is difficult to ascertain the likely wave and storm surge effects these events might have generated within van Diemen Gulf, it seems possible that the effect of one such abnormal event could have generated a temporary elevation in water level sufficient to breach the chenier ridges, levées and/or the upper floodplain protecting the low-lying freshwater environments and thereby allow saltwater access to the plains. It is less likely that the effects of any one such storm would have been experienced over the wide geographical region from which some tidal creek extension has been observed.
4.3.2. Rainfall variability

Analysis of rainfall data for the region (Cook & Russell 1983; Taylor & Tulloch 1985) indicated no clear correlation with the onset of creek extension (Woodroffe et al 1991). Nevertheless, periods of particularly high rainfall, and high floodwaters at the Mount Bundey water level recorder have occurred during the period when tidal creek network extension has been especially rapid (Jolly & Chin 1992). In view of the similarity of the creek network to river networks, in form and process of expansion, Wet season flows down the main channel and off the plains have almost certainly played some role in the creek excavation. In particular, headward sapping and extension of creeks just to the north west of Shady Camp during Wet season floods appear to have occurred as a result of overbank flows from Shady Camp Billabong and Red Lily Billabong (Fulton 1993).

4.3.3. Direct human effects

Anecdotal evidence exists concerning the dynamiting of chenier ridges during the 1970s in an attempt to improve access to barramundi fishing grounds. There is also a suggestion that the name Tommymcut results from artificial 'cutting' of a channel. The former practice seems to have been limited to one or two tributary channels off Sampan Creek on the eastern plains (Water Resources, pers. comm., 1992), while the latter is unsubstantiated. Local sources also suggest that the opening up of the Narrows section, downstream of Shady Camp, was the result of a deliberate effort to improve access within the creek network.

Several suggestions have been made that waves generated by boat wakes have accelerated erosion of the creeks (ie, Stocker 1970; Fogarty 1982). The expansion of the tidal creek system has been accompanied by rapid erosion of the creek banks as the creeks have widened (Woodroffe et al 1990; Knighton et al 1992). This is a natural co-adjustment to the increasing size of the network, and cannot be attributed primarily to boat traffic. The widening trend has been observed between each set of aerial photographs, starting at the creek mouths in the 1940s and 1950s, when boat traffic was presumably minimal. The pattern of change has been similar on both Sampan and Tommymcut Creeks, though boat traffic on Sampan Creek greatly exceeds that on Tommymcut Creek, and extension has occurred on tributary creeks whether accessible or not. Also, widening on the Mary River creeks, whether they be mangrove-lined or bare of littoral vegetation, far exceeds that observed on more popular boating creeks or billabongs (ie, Nourtangie Creek, Yellow Waters Billabong). Although deepening of critical sections, such as the Narrows, probably does reflect determined efforts of fishermen to get through, the overall widening trend cannot be due to boat traffic.

4.3.4. Buffalo Impact

Within the Northern Territory, one of the preferred explanations for the reversion to saline conditions within these coastal wetlands is the direct impact of large numbers of uncontrolled feral buffalo (Bubalus bubalis) (Fogarty 1982; Russell-Smith 1985; Applegate 1990). Buffalo numbers have declined in recent years as a result of a
Brucellosis and Tuberculosis Eradication Campaign (BTEC), however an estimated 341,000 (1.53 per sq km) animals were present in the area in 1985 (Bayliss & Yeomans 1989). There is little doubt that buffalo have adversely affected vegetation, soils, hydrology, water quality and the habitats of a variety of native fauna (Fogarty 1982). Of particular interest to the present discussion are the effects on coastal wetlands due to the physical activities of wallowing, pugging, slithering on banks and progressing along channels. Widespread pugging causes bare areas of soil in the Wet season, whilst in the Dry season it compresses the soils which then harden and often remain bare (Fogarty 1982; Taylor & Friend 1984). Slithering tends to break down the levée banks of the rivers and banks of channels and, together with movement along them, deepens channels (Fogarty 1982). Tidal saltwater intrusion into freshwater swamps and subsequent Melaleuca dieback can be caused by the further deepening and lengthening of channels from the tidal rivers across the sedgelands to the deeper swamps. Such channels are termed 'swim channels' and have been defined as the continuation of well defined trails in the woodlands, down which silt also passes from erosion caused by buffaloes (Williams 1976). Buffalo may also compact the surface sediments.

Correlation between the regional pattern of tidal creek extension and the variable distribution and relative abundance of feral buffalo has been inconclusive. Analysis of time series of aerial photographs of the Top End coastal plains suggests that saltwater intrusion has been extensive on the Mary River and the Alligator Rivers but has caused only minor changes along the Adelaide River. These observations accord with and extend the observations of Fogarty (1982) who noted extensive saltwater intrusion on the Alligator and Mary Rivers, while the wetlands of the Adelaide, Finniss and Reynolds Rivers had not been extensively modified. According to East (1990), the South Alligator has been characterised by the most extensive erosion in the region because of its larger area of erosion susceptible soils and landforms and high buffalo populations. Erosional features on the South Alligator are invariably associated with abundant evidence of buffalo presence, including wallows, pads, pugged ground and damaged vegetation (Ridpath 1991), providing compelling evidence, according to East et al (in press) of the causal link between buffalo and much of degradation in these areas.

Buffalo numbers appear to have been particularly high around the time that the creek networks began to expand. Annual hide production exceeded 6000 in the mid 1920s, and reached a maximum of more than 16 000 in 1937/8, before hunting declined. It seems likely that peak buffalo numbers coincided with the onset of creek expansion. The areas in which creek expansion has been observed, also correspond to those where buffalo are considered to have been concentrated (Fogarty 1982).

Apart from the identification of distinct 'swim channels' (ie, tributary channels intercepting other channels at right angles), it is difficult to establish the precise impacts of buffalo activity in causing saltwater intrusion on the Mary River plains. Fogarty (1982) suggests that heavy buffalo activity (eg, 35/km² on the Mary River in May 1981 (Graham et al 1982)) has likely hastened and in some cases initiated
channel development and hence saltwater intrusion. Stocker (1970) describes the breakdown of low shoreline banks and levees as a direct result of trampling, and also of heavy grazing by buffalo. Figure 34 illustrates the swim channel drainage pattern in the vicinity of Flood Mark and Fire Dreaming Islands to the south of Shady Camp. Swim channels on the plains often run at right angles to cheniers. However, examination of the 1943 and 1950 aerial photography provides no evidence for such a cause to explain Sampan and Tommymcut Creeks breaching the chenier ridges along the coast. Detailed investigation of the topology of expanding creek networks, particularly Sampan and Tommymcut Creeks described above, indicates an extremely regular pattern of creeks, similar in planform to fluvial channel systems, following a dendritic pattern of first order creek extensions, and density infill (Knighton et al 1992). This regularity suggests that, although buffalo may have triggered, and certainly hastened, the natural pattern of tidal creek expansion, in addition to having major impacts on the microtopography and vegetation of the wetlands, the tidal creek network has evolved in an organised fashion and cannot be entirely the result of buffalo damage.

4.3.5. Consolidation and compaction of plains

In the model of Holocene progradation, proposed in the previous chapter, saltwater was gradually excluded from these low-lying plains as they accreted vertically to a level at which the tide no longer reached them. This level would probably have been higher than 2.2 m AHD. Horizontal build-out of the coast would also have contributed to the exclusion of tidal waters from inland areas because of an insufficient gradient for water to flood across extensive horizontal plains (as discussed above in relation to saltwater flooding at lower elevations at greater distances from the main creeks).

The present pattern of saltwater intrusion represents the reinvasion of these low-lying, previously saline parts of the coastal and paleoestuarine plains. Surprisingly, however, many areas from which saltwater had previously been excluded, are now below the level of highest high water and hence subject to inundation under spring tides. If vertical sedimentation was responsible for raising the coastal plain above the limits of the tidal range, leading in turn to the disappearance of mangroves from much of the coastal plain, through a succession from *Avicennia* to saline mudflat to grass/sedgeland, as can be seen in horizontal transect at the present coast, then either an increase in the elevation of the high tide level, or a lowering of the plain has occurred to account for why the plain is now below highest high tide level.

Sea level has not risen during that time; in fact it has probably fallen slightly during the late Holocene. Relative sea level fall has been shown in the Gulf of Carpentaria (Chappell et al 1982; Nakada & Lambeck 1990), and is suggested at Cobourg Peninsula (Woodroffe et al 1992). It is possible that tidal amplitude has increased in van Diemen Gulf as the coast built out; Woodroffe et al (1986) suggested modification of tidal range along the South Alligator River as a result of Holocene
morphodynamic changes. However, sea level and tidal amplitude change should have cancelled each other out, and cannot be demonstrated from the geomorphological results available. Relative lowering of the plain surface is more likely.

It is possible that the sediments themselves have compacted since they were deposited. This issue was considered when compiling sea level data during studies of the South Alligator, but compaction was considered to be minimal because radiocarbon dates from the upper sections of drillholes, containing 10–20 m thickness of compactable muds, did not appear to differ in their elevation from contemporaneous samples taken from the base of shorter drillholes where they overlaid an incompressible bedrock (Woodroffe et al 1987). Despite this evidence, it is apparent that material is compressed by the weight of overlying sediment, and woody fragments from the transgressive mangrove facies are often compressed into elliptical forms. Subsidence is recognised in deltaic sediments, where interdistributary basins undergo breakup and inundation as a result, primarily of flexure of the crust under increased load, but also of consolidation and compaction. The rate of consolidation or compaction is unknown, but progressive consolidation and compaction would explain the relatively lower heights of the western levée and paleochannel surface compared with the eastern paleochannel.

4.3.6. Natural cycle of change

It is important to consider whether the present pattern of tidal creek extension is part of a natural cycle of saltwater extension that occurs with a regular periodicity. Natural extensions and contractions of tidal creeks have been demonstrated on the South Alligator plains (Woodroffe et al 1986). Past tidal systems have existed across the Mary plains, and this study has outlined the chronology of these. Former estuarine systems have not come about by the intrusion of a saline tidal creek system into the freshwater plains. Instead switching of systems in the past appears to have occurred primarily by avulsion of fluvial outflow, while tidal processes appear to have worked to infill these former paleochannels. Although there are paleocreek systems on the plains, these do not seem as widespread, nor as dendritic as the modern expanding system. Furthermore the evidence suggests that there has been no major estuarine outlet from the Mary River to van Diemen Gulf over the last 2000 years, although paleochannels were in various states of infill during this period.

Before dismissing natural cyclical change, it is necessary to consider what evidence would be preserved if paleochannel systems had been cut and filled several times as part of a natural cycle during the late Holocene. Two lines of evidence could indicate such reoccupation and abandonment: first, paleochannels might be identified within older paleochannels; and second, radiocarbon dates on one paleochannel might show different ages where different suites of infill had been dated. It is possible to identify two phases of paleochannel activity at two locations: paleochannel B occupies part of the course of paleochannel A, and paleochannel X occupies much of the course of paleochannel C. However, as discussed at length above, the form of the later channels (fluvially-dominated) differs from that of the former channels (tidally-dominated), and
radiocarbon-dating does not clearly identify these as two distinct phases. Paleochannels C and X, in particular, cannot be significantly differentiated on the basis of dates, and the younger channel has been interpreted as a fluvial channel which has persisted within a tidally-infilling estuary, prior to the avulsion of the system to another course. The range of ages on paleochannels A, B and D is broader; dates from paleochannel D indicate at least two distinct phases of activity. The broad spread of radiocarbon ages might be taken to indicate channel reoccupation, but this is unlikely, principally because two specific sites, Alligator Lagoon and the S-bends in Sampan Creek, have yielded ages which span the variation seen throughout most of the rest of the system. It may be significant that the older samples were collected at a later collection time from both sites, with a period of rapid erosion between collections. While this may have stripped younger fill, and exposed older fill, no morphological evidence for phases of stripping and infill at these sites can be seen on aerial photographs, despite the faithful preservation of paleochannel form for much older channels over the plains generally (as shown on the accompanying geomorphological map). A more probable explanation is that each site has infilled gradually over the 1000 years or more spanned by the dates.

In short, the geomorphological evidence gathered does not support the regular reoccupation of paleochannels, nor the past excavation of tidal networks through progressive extension of a dendritic system of creeks, as has been observed over the last 50 years.

4.3.7. Overview

This study has shown that almost all of the plains have been saline at some stage in the Holocene; that large estuarine paleochannels traversed the coastal plain; and that paleocreeks formed and have been abandoned. There is no evidence to suggest that the present phase of saltwater extension is part of a natural cyclical change in the system. The present pattern of tidal creek expansion does not appear to have direct parallels in the geomorphological history of the plains, and the coincidence of this phase on several systems indicates that tidal creek expansion was possibly triggered by some exogenous factor. The plains appear to be particularly vulnerable at this point in their history, perhaps because they have compacted since they were initially deposited. It is difficult to pinpoint the cause of recent changes, and there may be multiple causes, however, the fact that the plains have been more influenced by human activity during the last 50 years than at any time over the preceding 6000 years, is circumstantial evidence to suggest that the rapid change may have been triggered anthropogenically. Buffalo activity on the plains is the most obvious landuse change, anthropogenically induced. Rapid creek expansion appears to have been initiated at a time when buffalo numbers were particularly high. The coincidence of timing is not in itself proof that buffalo did initiate the change, nevertheless, whatever other causes there may have been, it will never be possible to totally exonerate buffalo in view of the very real degradation of the wetland environment that can be attributed to them. Whatever triggered the change, it has unveiled the incredible vulnerability of extensive areas of these floodplains that lie
below the highest level reached by tides in van Diemen Gulf, and which are being
intruded by a tidal creek system now expanding through a natural cycle of diffuse
saltwater inundation and tidal creek incision.

4.4. Tidal hydrodynamics of the Lower Mary River

Modelling the hydrodynamic processes involved in the development of the tidal creek
network of the Lower Mary River is important in order to establish the changing
interactions between tidal and fluvial flows, the processes involved in the
development of channel morphology, and the nature of sediment texture and sediment
movement. It may also allow the behaviour of the network to be simulated under
different management intervention strategies (location and effect of structural
controls), sea level change scenarios, and fluvial conditions. At present, however,
there are too few data to adequately understand the hydrodynamics of this rapidly-
evolving system, and far too few to calibrate a model. Preliminary results of some
observations of flow characteristics are reported here, based upon gauging carried out
in collaboration with the Water Resources Division of the Power and Water Authority
(Plate 14).

Plate 14 Monitoring the hydrodynamic behaviour of the tidal creek network involves
collaboration between the Land Conservation Unit of CCNT and the Water Resources
Division of PAWA
Gauging was undertaken in November 1991 during a late Dry season spring tide, in April 1992, to reflect the influence of Wet season fluvial floods (though due to the influence of ENSO this period had only minor freshwater inputs to the system), and in September 1992 to provide an additional spring tide gauging, also with no fluvial input. Data such as these are fundamental to the calibration and successful operation of a computer model which can simulate the complex processes involved.

Four gauging stations were established along the main channel of Sampan Creek and these are described in Table 7.

Table 7. Location of gauging stations along Sampan Creek

<table>
<thead>
<tr>
<th>Station</th>
<th>Code</th>
<th>Distance upstream (km)</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station 1</td>
<td>8180063</td>
<td>0</td>
<td>mouth of Sampan Creek</td>
</tr>
<tr>
<td>Station 2</td>
<td>8180062</td>
<td>15.5</td>
<td>immediately upstream of Roonees Lagoon</td>
</tr>
<tr>
<td>Station 3</td>
<td>8180061</td>
<td>23.0</td>
<td>immediately downstream of the S-Bends</td>
</tr>
<tr>
<td>Station 4</td>
<td>8180058</td>
<td>35.2</td>
<td>350 m downstream of Shady Camp</td>
</tr>
</tbody>
</table>

Initial monitoring in November 1991 confirmed that the water level recorder at Shady Camp is representative of conditions at station 4. Portable tide gauges were installed at stations 1, 2 and 3 in April 1992. These consisted of MINDATA 5-metre strain gauge pressure transducers connected to SDS digital data loggers. As a result of instrumentation failures and problems, only intermittent records were obtained between April and September 1992. However, a continuous record was available from September 1992. The latter includes complete lunar cycles and is suitable for the determination of tidal planes (i.e., changes in tidal height with distance upstream). These are currently being determined by the Manly Hydraulics Laboratory (MHL) in Sydney and will prove useful in several respects. They will identify any inconsistencies in data or problems with datum; assist in optimising the locations of the monitoring stations; and show how energy is dissipated with distance upstream. Harmonic constants will also be determined by MHL and add to the database of tides along the Top End coastline.

Stage observations at the mouth of Sampan Creek (station 1) are compared with the tide gauge in Darwin Harbour in Figure 9, indicating that tidal amplitude (November 1991) is considerably less at the mouth of Sampan Creek (5.0 m) than it is in the Harbour (7.8 m). Both records have been reduced to AHD; the delay of high water is 1.5–2.0 hours behind Darwin. Of the two high tides in the record, the higher reached a similar level to that in Darwin, but the lower was damped by about 30 cm. Low tide on the other hand is considerably higher in Sampan Creek, and presumably reflects the inability of the system to drain entirely at low tide. The result is that mean tide level is almost a metre higher than in the Harbour.
Gaugings were performed simultaneously at the four stations over complete tidal cycles. Gaugings commenced as close as possible to the peak of the flood tide and continued to the peak of the next flood (12–14 hours). Velocities were measured using an Ott impellor type current meter suspended from a boat. Between 5 and 10 observations were made across each gauged section, taking care to ensure that tidal stage did not change significantly from one side of the channel to the other and so affect the accuracy of the gaugings. Vertical profiles were also observed at 0.2, 0.6 and 0.8 of the depth from the surface. Upstream stations showed no significant vertical variations in velocity and observations were reduced to 0.2 and 0.8 of the water column depth.

The extent of tidal modification due to frictional dampening and boundary reflection near the mouth of Sampan Creek is not known, however, temporary tide gauges further inland indicate the extent of attenuation and/or distortion of river tides by passage upstream (Figure 9). The latter exerts a fundamental control over current velocities, rates of sediment transport and hence channel formation. The tide moves along Sampan Creek as a progressive wave, with a decrease in amplitude and an increase in asymmetry along the river.

The tidal prism at the mouth of Sampan Creek varied considerably over the three monitoring periods despite all three being within spring tide range (>4.0 m). Each period was also characterised by different ebb/flood tidal prism asymmetries. The flood volume at the mouth of Sampan Creek was almost twice that of the ebb volume in November 1991 while the ebb volume was greater than the flood through the mouth in April 1992. The ebb/flood tidal prisms were almost symmetrical in September 1992. The upstream decrease in tidal prism was particularly significant in November 1991 when less than 10% of the flood volume which had entered at the mouth reached station 3. The slightly higher tidal prisms recorded in April 1992 are due to minor fluvial inputs to the system (25 cumecs of freshwater recorded over the Shady Camp Barrage), at which time there was a pronounced ebb dominance at each of the stations.

All of the gaugings were associated with asymmetric hemicycle durations. Combined ebb and flood durations (one tidal cycle) varied between 11.5 and 14 hours (Table 8). Duration of the ebb tide was greater than the flood tide in all cases except at the mouth in November 1991 when a particularly large flood volume entered the system. This asymmetry in duration increased upstream; the ebb tide ran for up to 3 hours longer at station 3 compared with a 1 hour difference between ebb and flood at the mouth.
Table 8. Summary of measured tidal parameters\(^1\)

<table>
<thead>
<tr>
<th>Station</th>
<th>Spring tidal range (m)</th>
<th>Ebb tide duration (hours)</th>
<th>Flood tide duration (hours)</th>
<th>Ebb tidal prism (Mm(^2))</th>
<th>Flood tidal prism (Mm(^2))</th>
</tr>
</thead>
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<tr>
<td>23/11/91</td>
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<td>4.61</td>
<td>6.5</td>
<td>7.5</td>
<td>5.9</td>
</tr>
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<td>7.5</td>
<td>6.5</td>
<td>2.8</td>
</tr>
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<td>1.4</td>
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<td>8180063</td>
<td>4.00</td>
<td>7.0</td>
<td>5.0</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>8180062</td>
<td>4.20</td>
<td>6.8</td>
<td>5.0</td>
<td>4.1</td>
</tr>
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<td></td>
<td>8180061</td>
<td>2.55</td>
<td>7.0</td>
<td>4.5</td>
<td>2.4</td>
</tr>
<tr>
<td>29/3/92</td>
<td>8180063</td>
<td>4.18</td>
<td>7.0</td>
<td>6.0</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>8180061</td>
<td>2.89</td>
<td>6.5</td>
<td>5.0</td>
<td>1.6</td>
</tr>
</tbody>
</table>

1. Data: Water Resources, NT

The ebb/flood duration asymmetry produced a corresponding asymmetry in ebb/flood instantaneous tidal discharge and ebb/flood current velocities. Maximum instantaneous velocities at the mouth were similar for both ebb and flood tides in November 1991. However, as Figure 39 shows, the flood tide maintained higher velocities for longer. This was expected given the much greater tidal prism and duration of the flood tide over this time. Ebb velocities were higher at the mouth in April 1992 and had a longer duration, resulting in a larger ebb tidal prism. Ebb/flood velocities were almost symmetrical in September 1992 consistent with the more symmetrical hemicycle duration and tidal prisms of this period. Mean velocity is plotted against tidal stage in Figure 40.

Preliminary calculations of tidal discharge (Figure 41) indicate that tides become increasingly asymmetrical with distance upstream. The shorter flood tides and longer ebbs are most likely due to frictional effects produced by low tide amplitude/channel depth ratios. Overbank flow and tributaries contribute to longer ebb durations. They also add to the large loss in flood volumes with distance upstream, together with changes in tidal prism. For example, in November 1991 only 10% of the flood tide prism at the mouth reached station 3, much of the flood volume having been absorbed into the tidal creek networks in the downstream parts of the system. Conversely, relatively more of the flood volume reached the upstream gauging stations in April 1992 because the lower tidal range resulted in less tidal water extending up into adjacent tidal creeks or spilling out as overbank flow. Only a small proportion of the total volume entering the system reaches Shady Camp but the volume of this water does not appear to vary significantly under different tidal conditions. At present it seems that the effect of the higher tides is largely absorbed within the downstream parts of the network. There are additional losses due to infiltration and evaporation.
Figure 39  Mean velocity variation over time for three gauging stations along Sampan Creek gauged over three different spring tidal cycles (data: Water Resources Division, NT)
Figure 40 Mean velocity variation as a function of tidal stage for three gauging stations along Sampan Creek gauged over three different spring tidal cycles (data: Water Resources Division, NT)
Figure 41 Discharge variation over time for three gauging stations along Sampan Creek gauged over three different spring tidal cycles (data: Water Resources Division, NT)
The resultant upstream and downstream sediment transport depends strongly on the degree of tidal asymmetry and the relation between tidal prism and Wet season fluvial flood discharge. Although the system shows a foreshortening of the flood tidal limb, there is not the associated increase in velocity characteristic of other larger macrotidal estuaries, whereby the flood velocities exceed the ebb velocities, and which could result in a net resultant upstream potential for sediment transport (i.e., in the South Alligator: Woodroffe *et al.* 1986; Vertessey 1990).

A pilot sediment gauging exercise was carried out in September 1992 to assist in understanding local sediment budget and to determine net sediment movement. Suspended solid concentrations, electrical conductivity (EC) and temperature observations were carried out at the mouth of Sampan Creek (station 1) and downstream of the S-Bends (station 3). Samples and observations were taken at 0.25, 0.50 and 0.75 of the distance across the gauged channel section and from 0.2, 0.6 and 0.8 of the depth below the water surface. This was repeated several times throughout the tidal cycle.

Suspended sediment samples were collected by attaching a small submersible pump below the current meter. Water was then purged through the line and collected in pre-washed one litre sample bottles. EC and temperature readings were taken on site using digital instruments. EC standards were used to confirm correct calibration of conductivity meters before each measurement. Total suspended solids (TSS) and volatile suspended solids (VSS) were determined in the Water Resources Laboratory within three days of sampling. Results are shown in Figures 42 and 43.

![Graph showing sediment concentration versus time](image)

**Figure 42** Sediment concentration and its variation over a tidal cycle as two sites on Sampan Creek
Figure 43 Sediment budget and its relationship to tidal discharge over a tidal cycle at the mouth of Sampan Creek and at the S-bends (data Water Resources Division, NT)

It is estimated that the flood tide carried about 7000 t of sediment upstream at the mouth and that the ebb tide carried about 5800 t downstream, a net import of 1200 t; whereas at station 3 there was a net downstream movement of sediment. These results are only preliminary and cannot be used to extrapolate longer-term budgets. Nevertheless, they demonstrate the potential of tidal asymmetry to generate net upstream or downstream movement of sediment. The net budget will have changed markedly as the system, and its hydrodynamics, evolved over the last 50 years.

Channel cross-sections were measured in the field, in collaboration with the Land Conservation Unit of CCNT, using standard surveying techniques and an echosounder mounted in an aluminium dinghy (Plate 15). A total of 42 cross-sections were surveyed (Figure 37). Of the 19 cross-sections on Sampan Creek, 9 were later tied into AHD, including the 4 gauging stations.

Figure 44a demonstrates a distinct exponential decrease in cross-sectional area with distance upstream. There are two outliers, cross-section SCM12 at Shady Camp, which reflects the influence of the Barrage, and cross-section SCM03 near the mouth of Sampan Creek which seems to be at the site of a chenier breach. Figure 44b illustrates the change in hydraulic radius, a surrogate for depth, with distance upstream. The trend is similar to the previous plot with sections SCM03 and SCM12
as outliers in an otherwise linear relationship. Figure 44d plots distance against width/depth ratio and shows a distinct shift in the trend. A very linear relationship exists from the mouth as far upstream as 23 km. Beyond that point there is no relationship. A similar trend is shown in Figure 44c which plots distance upstream against bankfull width. The point of transition from a linear to a non-linear relationship coincides with the S bends reflecting the extent of the control exerted by inherited channel morphologies on tidal river morphodynamics. Strong tidal dampening also occurs at the S Bends and through the Narrows, although additional monitoring is required to confirm the extent of this.

**SAMPAN CREEK**

**Figure 44** a: Change in cross-sectional area with distance upstream along Sampan Creek; b: variation in hydraulic radius with distance upstream along Sampan Creek; c: variation in bankfull width with distance upstream along Sampan Creek; d: variation in width/depth ratio with distance upstream along Sampan Creek (numbers represent sequence of cross sections shown on Figure 37 with distance upstream)
The relationships shown suggest that the hydrodynamic behaviour of the system is actively evolving towards a quasi-equilibrium condition with respect to channel geometries. Even section SCM02 within Sampan Billabong, despite being an outlier in terms of its width and depth dimensions, conforms to the linear upstream relationship with respect to its area. Such relationships are fundamental to understanding the current pattern of change within the network and to predicting the nature of likely future changes.

Surveyed channel cross-sections (Figure 37), and demonstrated upstream changes in tidal asymmetry, are consistent with the patterns and rates of tidal tributary development proposed from the historic reconstruction of the network (Woodroffe et al 1991, Knighton et al 1992). For example, maximum channel depths within Alligator Lagoon (SCP1-8) are less than 2.5 m compared with maximum depths of between 5–6 m in the main channel (SCM08, SCM014). Spring tidal range at station 2, approximately 4 km downstream of the confluence between Alligator Lagoon and Sampan Creek, is 4.2 m which suggests that tidal waters can only penetrate Alligator Lagoon at relatively high tidal stages. The surveys also indicate
that the gradient within Alligator Lagoon is very low (max depth at SCP2 is 2.2 m, SCP6 is 2.5 m and 2.4 m at SCP8) so that there is very little head of water and tidal waters consequently drain (ebb flow) slowly.

Further upstream, where tidal creeks have almost linked between Sampan and Tommymcut Creeks, cross-sections show that these tributary creeks are only 1.5–1.75 m deep (SCS13, SCS21) while Sampan Creek is about 4.5 m deep (SCM013, SCM010) and the spring tidal range (Station 3) is 3.3 m. Similarly, at site SCS12 on the eastern bank of Sampan Billabong the creek has a maximum depth of only 1.5 m and remains perched above the main channel until inundated by the higher tides. Site SCS11, within the broad paleochannel that extends due north from Shady Camp billabong, is 1 m deep compared with a maximum depth of 2.5 m within the adjacent Narrows section.

Tidal flows in the complex dendritic creek networks of the Lower Mary River are clearly a function of channel morphology. Figure 9 illustrates the progressive deformation of tidal stage variations with distance up Sampan Creek. Tidal amplitude (and the elevation reached by high tide) decreases upstream while tidal asymmetry increases upstream. Changes in channel morphology lead to changes in the characteristics of tidal flows. The morphology has changed and is continuing to change rapidly in the case of the Mary River tidal creek networks, as has been shown above. Consequently tidal hydrodynamics must be rapidly evolving also.

The major morphological change involves lengthening and widening of tidal creeks. A likely hydrodynamic response is shown schematically in Figure 45. The fluctuation of tidal stage (water level) is likely to reflect that of the open gulf at the mouth of the creek. However, at t1, when the creek is only small, there is likely to be a substantially lesser tidal amplitude at a point Y in the creek headwaters than at the mouth. Tidal stage will be delayed and markedly asymmetric (with a small tidal prism). When the creek lengthens and widens (and deepens) tidal amplitude can increase and the height of the highest tide is likely to increase, but asymmetry will decrease. Deepening of the creek allows amplitude to increase and means that mean tide level may actually decrease. Nevertheless if the tides were reaching bankfull at Y at t1, they may overtop the banks at t2. Tidal flows, in turn, control patterns of erosion and sedimentation and hence morphology, so that in practice there is a mutual co-adjustment of form and process.
Figure 45 Schematic representation of the modification of tidal hydrodynamics as tidal creek system expands [Note less dampened tidal cycle with increase in amplitude and highest tidal level and decrease in asymmetry at t2 compared with t1, at point Y. Mean tide level decreases as creeks deepen]

4.5. Summary

1. There have been marked changes in the configuration of the coast and in the distribution of mangroves over the last 50 years. Erosion and retreat appears to have dominated, especially to the west of both Sampan and Tommecut Creeks, but build-out has also occurred locally.

2. The spectacular exponential expansion of Sampan and Tommecut Creek networks since the 1940s has occurred in a regular manner with elongation and elaboration of the network and increases in creek cross-sectional areas occurring
simultaneously as the tidal prism increased, except for isolated instances where
swim channels have been occupied, or freshwater billabongs invaded.

3. This expansion phase appears to have been triggered simultaneously on Sampan
and Tommymcut Creeks prior to 1943, and has been observed on several other tidal
systems in the area, although less spectacular, over a similar period of time.
Whatever the circumstances of the initial breach, the combination of a large tidal
range and the minimal relief of these plains, where extensive areas are lower than
the highest levels reached by the tide, provided an ideal environment for extensive
inundation of these systems by saltwater.

4. Tidal creek expansion does not appear to have resulted from any perceptible
increase in sea level, and although a storm surge may have breached the cheniers,
storms in that period were not exceptionally severe, and seem unlikely to have had
an influence over such a broad geographic area. The regional nature of change
(though by no means occurring on all estuaries) also rules out direct human
effects. Consolidation and compaction of the plains since their deposition seems a
likely explanation for why such large areas occur at elevations vulnerable to
saltwater inundation. However, it does not explain why change was triggered in
the 1940s.

5. Buffalo activity on the plains is the most obvious landuse change that has occurred
and coincides in timing and distribution with the period of rapid tidal creek
expansion. Coincidence of timing does not prove that buffalo were the cause of,
or trigger for, the changes, but buffalo cannot be exonerated in view of the
degradation they have exerted on these plains.

6. The plains have undergone extensive changes throughout the Holocene, however,
there is no evidence to support the view that the recent pattern of change is a part
of a natural cycle. Past changes in channel courses appear to have occurred by
channel switching rather than by the expansion of a dendritic creek network, as at
present.

7. Preliminary observations on tidal hydrodynamics confirm that tidal flows, and the
fluviotidal balance, are actively evolving as the creek system expands and
abstracts. Significant changes in tidal amplitude, flood/ebb asymmetry, and
patterns of net sediment flux have occurred in the past and will continue to occur
in the future. More data are required on these in order to monitor impacts, and to
calibrate hydrodynamic models.
5. MANAGEMENT OF THE LOWER MARY RIVER PLAINS

In this chapter an attempt is made to forecast the direction of future change on the plains of the Lower Mary River, based upon those changes that have recently occurred. It is important to recognise that the system is, and always has been, naturally dynamic, and that the most successful management practices will be those that accommodate the natural dynamics of the system rather than those that endeavour to preserve the status quo. There is a need to improve our understanding of the hydrodynamics of the evolving tidal creek network, by extending recent tidal monitoring, undertaken in collaboration with the Water Resources Division of the Northern Territory Power and Water Authority. A number of areas of the plains appear particularly vulnerable, and efforts to prevent further saltwater intrusion should be directed at those areas and given a high priority within an integrated planning approach for managing the wetlands. Acceleration in global sea level rise, should it occur, as a result of global warming, is likely to exacerbate the present problems. There is a need for flexible options for the sustainable management of changing wetland resources, and to ensure the most appropriate approach to management intervention is being taken.

5.1. Future expansion of tidal creek network

The pattern of tidal creek extension over the last 50 years has been outlined. The magnitude of the creek system of both Sampan and Tommycut Creeks has increased exponentially, and seems likely to continue to increase, over future decades. Two basic patterns can be observed in this recent extension. First, the creek system is still extending rapidly in its middle reaches filling the area between Sampan and Tommycut Creeks. Extension has been most rapid within a low-lying basin, mapped as lower coastal plain or, where characterised by dieback, as inland saline basin, surrounded by higher ground associated with the levees of paleochannels. Most of the low-lying areas have now been invaded, and the more seaward part of the network seems to have passed through the phase of extension, and in places to have changed into abstraction. Second, there has been extension of creeks around the present tidal limit, and in particular Wet season scour has been implicated in promoting headward extension of creeks to the north-west of Shady Camp. This extension is of concern because tidal penetration over the plain as diffuse flow cannot be the initial route of intrusion, as the plains here are considerably higher than the highest level reached by the tide.

Mangroves will continue to extend their range, colonising new creek extensions, and penetrating further up Sampan and Tommycut Creeks, as has been observed in recent years (Plate 6). This inland mangrove, particularly Sonneratia lanceolata and Avicennia marina, should stabilise banks somewhat, encapsulating tidal flows, and decreasing the rate of bank erosion. However, both species are associated with
slumping in deep but narrow creeks on other tidal systems, and at first their role may only be ephemeral in protecting banks within the Mary River system.

Examination of past tidal systems on the Mary River plains can offer some insights into how the system might look in the future. The creek network can be expected to continue to expand, both through elongation, and elaboration. Creeks will continue to widen throughout the system, and there will be further rapid reoccupation of paleochannels, both those already invaded and those not already exploited. This is likely to continue until an equilibrium is reached. This equilibrium will probably be determined partly by the drainage density of creeks on the coastal plain; in the past when a network density of 10 km/km² has been achieved, abstraction of creeks has been observed (Knighton et al 1992). The main creeks, Tommycut and Sampan, will probably continue to widen until they comfortably accommodate Wet season fluvial flow as well as the tidal flows that are required to fill the enlarged tidal prism.

The present tidal system is much smaller than the large estuarine paleochannels A and C (Figure 25). It has expanded recently at a rapid rate, but it is unlikely that it will re-excavate a channel of the dimensions of these paleochannels. The fluvial type paleochannels (B and X) are more uniform in width, and taper more gradually (Figure 46). The present main creeks of both Sampan and Tommycut taper at much the same rate, but are narrower than paleochannels B and X.

![Figure 46](image) Comparison of the exponential tapering of paleochannels, and of the expanding tidal channels
If the fluvial paleochannels represent a stable state which the system has adopted in the past, and if boundary conditions remain unchanged (i.e., climate does not change), then the network may cease to expand when it has reached that size. If, on the other hand, the estuarine paleochannels represent the stable state towards which the system is expanding, then considerably more erosion and channel widening will need to take place. The strongest argument in favour of the former suggestion (i.e., that the fluvial discharge of the Mary River will be accommodated within channels about 150–200 m wide), is that there is no evidence of a channel of estuarine paleochannel dimensions having been active in the last 2000 years. Even at equilibrium, bank erosion and slumping matched by deposition elsewhere, will continue. On that basis, the present Sampan Creek may continue to widen until it reoccupies the full width of paleochannel B within which it sits for much of its course through the coastal plain.

5.2. Vulnerability of the plains south of Shady Camp

The constriction between Alligator Head and Shady Camp has not acted to exclude saltwater from the paleoestuarine plain in the past, and there seems no reason why tides would not extend headwards into this plain if left uncontrolled. There is little information on the absolute height of the plain south of Shady Camp, however, a very gradual increase in elevation is indicated from the fact that there are floodplain muds of 1 to 3 m depth overlying the estuarine muds deposited beneath mangrove forests. Survey heights between Alligator Head and Shady Camp (Figure 11; profile L1-L2) suggest that most of this area is below 2.5 m AHD, and thus below the highest tide level at the coast. Tidal amplitude is considerably dampened at Shady Camp (Figure 9), but will continue to increase as the tidal channels get larger. At least some of the lower-lying areas of the paleoestuarine plain, principally paleochannels, are below the present high tide level at Shady Camp; areas below 2.0 m AHD are at particular risk. Considerably more extensive areas would be at risk if the tide reached Shady Camp undampened.

If the Shady Camp Barrage is not maintained, or is removed, salt will inundate Shady Camp Billabong, and make its way upstream. Though no evidence has been found for mangrove in this region since 4000 years ago, part of the paleochannel system has almost certainly been tidal through this constriction, possibly related to tidal flows through the western paleochannel. Radiocarbon dating of the transition period, shown by pollen analysis, is generally not possible because oxidation of the upper part of the record has removed organics suitable for dating.

Figure 47 is a schematic diagram based upon aerial photographic interpretation of the stages of saline intrusion into Sampan Billabong, which may provide a geomorphological analogue for what would occur should the Shady Camp Barrage be breached or removed. At t1, tidal flow does not penetrate into the freshwater billabong. At t2, either because of tidal creek extension in the case of Sampan Billabong, or breaching of a barrage, saltwater gains entry to and rapidly extends headward through the previously freshwater billabong.
Figure 47 Schematic interpretation of four stages in saltwater intrusion into a freshwater billabong, based upon Sampan Billabong

The morphology of the billabong is out of equilibrium with tidal flows and, at t3, encourages sedimentation of poorly consolidated saline muds. In the case of Sampan Billabong, it has been shown in the section on hydrodynamics that the cross-sectional area is in quasi-equilibrium with tidal flows, but that the channel is uncharacteristically wide. If the tidal network continues to expand, at t4, the channel would be likely to both widen and deepen as the tidal prism increases.

In the case of saltwater penetration into Shady Camp Billabong, there is presently insufficient survey data to assess the likely implications for the plains further south. However, as can be seen on the accompanying geomorphological map, there are networks of paleochannels, existing channels, and extensive areas of lower floodplain and backwater swamps close to Shady Camp, which must be presumed to be at risk of saline intrusion unless it can be demonstrated that there are areas of high enough ground, particularly levées to exclude salt from them.

5.3. Potential acid sulphate soils

A major conclusion of this study is that the bulk of the plains are underlain by sediments deposited in a saline environment. These sediments have a high salt content, but they are also potential acid sulphate soils. Low acidity and high soluble
aluminium contents of waters issuing from such soils can be a major problem where these areas are not managed wisely. They can account for death of plants, fish kills, or fish diseases such as red spot.

Acid sulphate soils are particularly associated with pyrite-rich sediments that have developed beneath mangrove forests. The pyrite has been produced from sulphate in sea water, which has reacted with iron, through the activity of organisms (plants and bacteria). When the pyrite which has been preserved in anaerobic sediments is oxidised it converts to jarosite and sulphuric acid, and may yield pH of 3.0 or less. Reactions with the clays also release aluminium, which can be toxic.

Oxidation of pyrite is occurring naturally, and can be seen in the oxidised upper part of all cores, where the oxidation may have been going on for hundreds or thousands of years, and there is pronounced mottling, and plenty of jarosite. Natural fluctuations in the water table can flush acidic water with high aluminium into billabongs causing fish kills (as recorded in Kakadu). However, the potential exists for rapid oxidation if large volumes of such sediment are exposed through excessive drainage, or due to excavation.

The likely extent of the problem can be gauged from the geomorphology. Big swamp mangrove facies probably have the highest levels of pyrite; thus the most serious problems are likely to be encountered from those sediments below the paleoestuarine plain. These are partly protected by accumulations of 1 metre or more of freshwater clay over the top. Coastal plain sediments are generally not as rich in mangrove remains and are probably lower in pyrite, but they are capped by less, if any, freshwater clay. It is quite possible that some of the death of *Melaleuca* that has been observed results from better drainage and lowering of the water tables. Elsewhere (especially on the South Alligator) areas of *Melaleuca* appear to have died because tidal creeks have allowed better drainage of freshwater from the area early in the Dry season, water tables have dropped, and potential acid sulphate soils have been oxidised.

Excavations, such as for earthen blocks, could aggravate the problem, though there is no evidence that problems of acidity have so far been experienced. Oxidation of sediment on barrages could also hamper revegetation of blocks.

### 5.4. Implications of future sea level rise

The extent of the saltwater intrusion problem is likely to be exacerbated if the sea rises as has been anticipated as a result of global warming in response to the 'greenhouse effect' (Gornitz *et al* 1982). This would have significant implications for the management of the area.

In 1987 a conference on planning for greenhouse-induced climatic change presented a scenario for possible climatic changes in Australia by the year 2030 (Pearman 1988). The scenario included an expected rise in sea level of between 20–140 cm. More recent predictions for global sea level change are in the order of about 20–30 cm by
2030, a rise of 5–10 mm/yr (Thom 1989, Houghton et al. 1990). It is also predicted that there will be changes in the magnitude/frequency of storm events.

The effects that sea level rise is likely to have upon the coastal wetlands of the Northern Territory have been reviewed by Chappell (1988, 1990). A small change clearly has the potential to inundate these very low-gradient plains causing them to revert to mangrove, samphire and saltflat (Chappell 1988), a trend that is already occurring on the Mary River as a result of saline intrusion through tidal creek expansion. The data presented in the previous chapters indicate that a major part of the coastal plain of the Lower Mary River is already at a lower elevation than the highest tides experienced at the mouth of Sampan Creek, and is already under threat primarily through changes in tidal hydrodynamics irrespective of any sea level change. There have been suggestions that the plains will revert to the mid-Holocene 'big swamp' (Press 1988), although such predictions take little account of compensating effects such as the development of natural levées, in which respect the present situation differs from the Holocene transgressive phase.

It is clear that the response of these coastal wetlands is only partly dependent upon the actual rate at which sea level rises, and is at least as dependent upon corresponding rates and patterns of sedimentation and hydrodynamic changes. Examination of past responses to sea level fluctuations can give us only some guidance as to what will happen in the future. The dramatic changes of the last 50 years on the Lower Mary River exceed most of the predicted impacts anticipated for such a coastal system over the next 50 years in response to accelerated sea level rise (Press 1988), despite the fact that no significant sea level rise can be demonstrated in the case on the Mary River (see chapter 4).

In order to understand the patterns of erosion and deposition of sediment under future anticipated higher sea level, the provenance of the sediments deposited on the paleoestuarine and coastal plains will need to be known with greater certainty than at present. If, as has been suggested above, tidal resuspension of marine muds and net landward transport have been significant factors in the past, then the response to sea level rise in macrotidal areas, such as the Mary River, may entail coastal and nearshore erosion and redistribution of sediments to build up the plains and add to tidal levées.

At present, there are large areas of freshwater wetland well below the elevation reached by the highest tides. The extent to which these will be able to survive in their current condition, in the face of accelerated sea level rise, will depend upon the rate at which vertical sediment accretion occurs to the levées relative to the rate of sea level rise. Neither of these rates are known with any confidence at present. However, any increase in tidal prism associated with sea rise, will accelerate the extension of the tidal creek system, exacerbating the diffusion of saltwater across the plains and the incision of tidal creeks into additional low-lying areas. A better understanding of sediment dynamics and the evolving hydrodynamics will be essential to manage wetlands effectively under these circumstances.
At this stage, rates of sea level change are low or imperceptible in the Top End, and as there will be considerable variation from site to site in the rate at which global sea level rise will be experienced locally (as there has been in the patterns of sea level change during the Holocene), there is still no certainty that the sea will rise with respect to the Top End. Furthermore, global rates of sea level rise, projected for future decades, have been through a number of downward revisions, as various contributing factors are reviewed (Oerlemans & Fortuin 1992). At present global predictions are too imprecise and unsubstantiated to justify any action solely designed to ameliorate the impact of future sea level rise. However, though problems on sites such as the Mary River have not been caused by sea level rise, the solutions which can be found to saline intrusion in such areas may have much wider application should other similar areas become threatened by saltwater intrusion as a result of sea level rise.

At this stage, protection structures, such as earthen blocks, should be designed to accommodate flood levels determined on the basis of existing data, recognising that there is only a short period of record for most data, and that design needs to incorporate events of a recurrence interval that are unlikely to have been experienced in the period of record. Monitoring of the response of these (i.e., settlement rates) can then allow their heightening during renovation, if a credible prediction for sea level change in the Top End can be determined; if tide gauge observations (such as the state-of-the-art tide gauge recently installed at Darwin by the National Tidal Facility) indicate a rising trend; or if other factors, such as an increase in high-tide level due to the evolution of the network hydrodynamics, become apparent through monitoring, or modelling. On the other hand, it would be prudent that any major new development on the plains or around the plains margin take the possibility of sea level rise into account in planning, and particular attention be paid to elevations with respect to AHD, as plains and plains, margin sites could be well below high tide level at the coast.

5.5. Existing management intervention strategies

The Mary River plains are recognised as having high aesthetic, conservation and recreation value as well as representing some of the most productive pastoral land in the Northern Territory (Applegate 1990). Integrated or Total Catchment Management is currently being adopted within the Lower Mary River (Sterling 1992), a process which should assist in more appropriate management and ecologically sustainable utilisation of the area. The plains currently support a wide range of land use, endorsing the Territory Government's concept of multiple land use.

At present, management intervention along the coastal and estuarine plains of the Mary River involves exclusion of feral buffalo, controlled stocking, designation of conservation areas and close monitoring of local pastoral practices. Further intervention may form a part of the implementation of an integrated catchment strategy, being developed by the Northern Territory Government.
Measures to control tidal creek extension initially involved simple control measures by local landholders. In 1987, the Land Conservation Unit of CCNT, in recognition of the seriousness of the threat imposed by saltwater intrusion, instigated a major restoration program to prevent further saltwater intrusion and the rehabilitation of salt-affected areas (Sterling 1992). The majority of barrages constructed since that time consist of simple earthen dams across the smaller tidal channels. The barrages have also increased access onto the plains by allowing vehicular traffic across the channels (Plate 16).

Barrages constructed within the Mary River Conservation Reserve are concentrated first along the coast where they straddle creeks which breach one of the more major chenier ridges, and secondly along the eastern levée to the western paleochannel (Plate 17), where they are aimed at keeping saltwater out of that paleochannel (Sterling 1992).

The Conservation Commission has also constructed, and maintained since 1988, the Barrage — a major concrete and rock structure on the natural rock bar at Shady Camp (Plate 1). Located approximately 30 km inland, the Barrage is designed to prevent saltwater moving upstream during the Dry season while reducing drainage of freshwater from the floodplains during the Wet season (Applegate 1990).

Plate 16 Recently constructed minor blocks in the area to the west of Shady Camp to curb the further extension of tidal creeks and improve access to the plains
The entry of saltwater into the upper reaches of the Shady Camp Billabong has been successfully halted since 1988 when the salinity of the billabong was reported as greater than that of seawater (Applegate 1990). The site of the barrage is now a popular recreational fishing, camping and amenity area within the Top End.

Construction of the barrages and many of the smaller earthen dams across several actively extending creeks appears to have successfully checked saltwater intrusion into many parts of the freshwater wetlands. The barrages are generally constructed to an elevation of 80 cm above the surrounding plains, settling to around 50 cm after their first Wet season. Earthen barrages are usually about 3-4 m wide to minimise the risk of breaching by freshwater floods at the end of the Wet season. Sterling (1992) has described their multiple role in combating land degradation, firstly through the prevention of saltwater incursion onto the plains in the Dry season, and also by promoting infill of active tidal channels. The barrages also aid in the retention of freshwater at the end of the Wet season thereby preventing premature drainage and the flushing of salts from the soils. However, the retention of freshwater is also a problem for many landholders as it delays access onto the plains during the Dry season putting extra pressure on upland grazing pastures. Thus barrage design must accommodate the very delicate balance required (I Fulton, pers. comm., 1992).
A number of other problems are associated with barrage construction. Firstly, design problems have arisen because of the dispersive nature of the black cracking clays used in their construction. The nature of the local environment and availability of funding, inhibits the use of more suitable material (Sterling 1992). Secondly, Wet season floods exert considerable pressure on the barrages resulting in breaching and failure of many structures at the end of the Wet season (Fulton 1993). There is a high cost associated with restoring and maintaining these barriers each Dry season, with logistical constraints imposed by poor access to the plains after the Wet season. Changing the inundation and drainage characteristics of parts of the plains may also alter the ecology of those areas, changing the plants that can grow there, or their suitability as wildfowl or fish habitats. The complex interrelationships and delicate balance between the physical and biological aspects of the plains are increasingly being accommodated by improvements in the design of barrages and earthen blocks. Further research is needed on the ability of littoral mangroves to encapsulate the system and encourage the system's ability to heal naturally. The suitability of various wetland species in aiding block stabilising, and in binding unvegetated muds should also be investigated.

Successful cases of barrages and dams containing saline intrusion are those barrages which have encapsulated creek headwaters, encouraging saline mud deposition on the downstream side, often with rapid mangrove colonisation. Examples of this can be seen on barrages across creeks which have breached the chenier ridge to the northwest of the coastal plain. In some cases, barrages have been less successful and the creek has actively cut around them. The success of the barrages seems to depend upon the location of the barrage within the creek network and the energy of the resulting hydrodynamics.

A hydrodynamic model would greatly assist in establishing the most effective locations for siting future barrages. In the meantime it is interesting that in some cases where barrages have been cut around, they still appear to be effective in limiting saltwater incursion. An example is the creek which has cut back into a paleochannel at Red Lily Lagoon, and which appeared to be threatening to circumvent the Barrage at Shady Camp by extending through the Alligator Head–Shady Camp constriction following paleochannel G1 or G2 (see Figure 25). This has shown little extension since 1991, despite the fact that this barrage has repeatedly been washed out by Wet season floods and allows some saltwater past it (Plate 18).

The rapid devastation of freshwater wetlands that has occurred on the Lower Mary River plains is threatening still wider areas of the plains. An estimate as high as 35–40% has been suggested (Applegate 1990). Barrage construction (a relatively minor level of physical intervention) appears to be meeting with some success in combatting this saltwater intrusion. There is also a suggestion that the northern parts of the plains have approached, or are approaching, an equilibrium, and that the system may reach a naturally stable state in the not too distant future, though for much of the coastal plain this will be a condition dominated by tidal influences.
Plate 18 Tidal Creek with a paleochannel near Red Lily Lagoon [This creek had reached this point in 1991 but has not extended significantly since then, perhaps as a result of a barrage, despite being breached, further downstream]

A series of major physical works, involving intervention on a broader scale than at present, are considered below from a geomorphological perspective.

5.6. Options for future management Intervention

In this section five alternative major works options are examined in terms of whether they appear feasible from a geomorphological perspective. It is important to emphasise that none of these is being specifically advocated, and engineering advice and further hydrodynamic monitoring would need to be sought before any of these could be considered as viable options. The question of whether and how to interfere with the dynamics of such systems must also be answered by politico-economic decisions and such considerations are not discussed here.

It is also important that the implementation of a particular management intervention option or combination of options involves a integrated strategic approach to the management of the area, such as that embodied in the integrated catchment management strategy which is being developed, to minimise the problems and costs of ad hoc piecemeal intervention. The successful implementation of any strategy will
depend on the availability of adequate data on the use of the various resources and on the natural functioning of the environment. Major changes to any part of these natural systems are likely to cause immediate and sustained changes to other components and such feedback effects will need to be considered and planned for. Where possible management should work with and not against the natural functioning and anticipated pattern of change of the environment.

Five possible options for future management intervention include: i) exclusion of saltwater at the coast; ii) exclusion of saltwater from southern parts of the plains, south of the Shady Camp–Alligator Head constriction; iii) control or partial exclusion of saltwater near the coast; iv) artificial levées and embankments; and v) exclusion of saltwater from selected areas on the plains.

i. Exclusion of saltwater at the coast would preserve the maximum area of the plains, but a major scale of physical intervention would be necessary, possibly involving most of the Chambers Bay shoreline. It would probably be insufficient to build a major structure only at the mouth of Sampan Creek (Plates 19 and 20), as Tommycut Creek already connects with Sampan Creek at its upstream end, and would presumably expand to become the major tidal route if Sampan Creek was blocked. Structures at the mouths of both Sampan and Tommycut Creeks might also prove to be only a temporary solution as the possibility exists that another tidal creek might expand inland. The tidal creek to the west of Tommycut Creek appears, from aerial photography, to have been connected to the western paleochannel in 1943; it might reverse the capture of its headwaters by Tommycut Creek by in turn capturing the Tommycut tidal creek network. There are instances where engineering works of comparable scale have been constructed (i.e., the Thames Barrage in London; or the system of dykes along the coast of the Netherlands), where similar engineering problems associated with building on unconsolidated mud have been encountered, but these structures tend to be designed to keep tidal waters out of land with particularly high population densities.

ii. Exclusion of saltwater from the freshwater wetlands south of Shady Camp would preserve the high conservation and biodiversity status of these plains, and their tourist potential. This would require a physical structure to be constructed from Shady Camp to Alligator Head, or to some similar bedrock outcrop on the western side of this natural constriction. A structure of this sort was contemplated in the 1950s in order to aid irrigation of the Adelaide Plains (Water Resources Division files). However, the depth of unconsolidated sediments (>10 m), implies that construction would not be easy and such a structure would seem likely to cause more problems than it would solve. For example, it would be necessary to control the amount of freshwater released through or across this structure and if this was done inappropriately the ecology of both those areas to the south and to the north could be irreparably altered. Furthermore, such a structure would offer no protection to the coastal plain, large areas of which have not yet been invaded by saltwater.
Plate 19 Present mouth of Sampan Creek

Plate 20 Channel widening immediately upstream of mouth of Sampan Creek resulting in bank failure and the collapse of *Ceriops tagal*
iii. Control or partial exclusion of saltwater on the coastal plain is a more viable alternative to the total exclusion options presented above. Partial exclusion could be achieved by reinforcing the line of existing chenier ridges, inland of the present shoreline. These ridges may have offered rather more protection to the plains in the past, though it is unlikely that they provided an impenetrable barrier to tidal waters; rather, a subtle topographic feature would have built up to a level around the high tide which then hindered the incursion of the wetting front. The cheniers may have become less able to perform this function as a combination of consolidation/compaction of the plains; dissolution of shell from the ridge; general degradation of the surface as a result of buffalo activity; as well as breaching by occasional swim channels, all of which would have reduced the elevation of the ridges. Reinforcing the cheniers might involve further earthen blocks, similar to those already constructed at breaches occupied by tidal creeks or swim channels, with embankments at some sites to prevent sheet flow across the chenier. Some form of engineering would also be required to reinforce the cheniers where they outcrop in the banks of Sampan and Tommcut Creeks. These could usefully serve to gradually dampen tidal amplitudes over time rather than involving total blockage of these creeks. The latter would pose major engineering problems, and might also lead to long-term hydrological problems unless some means to drain Wet season floods were incorporated. The Adelaide River may provide a geomorphological analogue. The Narrows at the mouth of the Adelaide River is a bedrock outcrop which constricts the width of the channel. The tidal amplitude upstream on the Adelaide River is generally less than that on other similar-sized rivers (ie, the South Alligator River, Woodroffe et al 1986, Veterssey 1990). An artificial constriction near the mouth of Sampan and perhaps also Tommcut Creeks might similarly dampen tidal amplitude upstream.

iv. The construction of artificial levées and embankments presents a fourth option for large-scale physical intervention. The value of natural levées in keeping saltwater within the creeks was highlighted in earlier chapters. Such a strategy has been adopted in many river flood mitigation schemes, or in delta control, such as in the case of the Mississippi, where a major avulsion into the Atchafalaya River is being prevented by a structure built by the U.S. Corps of Engineers. Physical construction of levées and embankments is also practised extensively in the Sunderbans, the tidally-dominated part of the Ganges-Brahmaputra Delta. Enhancement of natural levées and construction of artificial levées will only be necessary where high water level overtops, or threatens to overtop, the bank and natural levée. By and large this is not yet the case and until it is, levées may only need minor enforcement with earthen blocks where breaches occur. This reflects the present management approach. A more large scale commitment to levée construction and enhancement, if it is required in the future, will pose major difficulties because of the extensive nature of the creek network and because of the local shortage of suitable construction material.
v. Exclusion of saltwater from selected areas involves prioritising areas of particular conservation, recreational, economic or other values. Again this option reflects existing management approaches, although it may require more formal designation of priority areas. This option might also be implemented in combination with options iii or iv, above. The identification of areas of greatest vulnerability, as outlined below, and highest priority will greatly assist in developing appropriate intervention strategies and minimise the extent of physical intervention required.

5.7. Identification of vulnerable areas

Saltwater is intruding into many areas of the coastal plain where it has not been present for hundreds or even thousands of years. The identification of areas of greatest concern and in need of most urgent management intervention should, as mentioned above, be undertaken as part of an integrated management strategy.

The following areas of particular vulnerability to saltwater intrusion can be identified. The western paleochannel is very vulnerable because it is so low-lying. It does not appear to have been reoccupied since it was abandoned over 3000 years ago. Saltwater would penetrate upstream rapidly, and it would also probably escape westward along the paleocreeks marked on the geomorphological map, which provide a route into the extensive *Melaleuca* stands on the west of the coastal plains, and are generally too wet for access but appear to be low in elevation, and almost certainly below highest tide level. These have a high conservation priority because of their role as important bird feeding areas in the wet season.

Particularly rapid expansion of the tidal creek invading Alligator Lagoon has occurred in recent years. This paleochannel can be traced to the eastern end of the Narrows, just north of Shady Camp, and is evidently the former course of a major estuarine paleochannel (paleochannel A). The rapidity of incision here suggests that the tidal river may reestablish paleochannel A as its preferred course, and in future years join up with Shady Camp through this route. The full consequences of such a change cannot be foreshadowed, but there might be some advantages to this becoming the main route for Sampan Creek. First, there appear to be well-developed levées along this paleochannel. Second, much of this area has been invaded by *Mimosa pigra* and hence is no longer productive or easily accessible. Third, it may reduce the volume of tidal water reaching creeks that are expanding at the upstream end of Sampan Billabong, specifically the creeks in the Red Lily Lagoon area. However, as these could also receive water through an expanded Tommyncut Creek system, the extent of tidal prism reduction may be limited or short lived. In addition, increased flows through Alligator Lagoon are likely to result in new saltwater intrusion problems on the eastern margin of the plains, with further dieback in backwater swamps to the east of Alligator Lagoon.

Further tidal creek extension in the area around the Shady Camp Barrage remains a distinct possibility, either as a result of headward erosion of the creeks feeding off just
below the barrage, or by extension of creeks along the other paleochannels which can be seen between Alligator Head and Shady Camp. The low-lying depressions F, G1 and G2 (Figure 25) offer what must be easy alternatives for flow. Wet season flows might scour out one of these routes, although there is little evidence to suggest that Shady Camp Billabong is likely to avulse into one of these courses in future years.

5.8. Recommendations for future management, monitoring and research

It is apparent that there are many elements of the geomorphology of the Lower Mary River which are still incompletely understood. Consequently the implications of management intervention remain uncertain. In the following section the major management issues are examined from a geomorphological perspective, future monitoring needs are considered, and areas which require further research are discussed.

5.8.1. Management

It is probably impracticable to consider total exclusion of saltwater from the plains in geomorphological terms. The coastal plain, in particular, has formed through nearshore marine processes and has always retained some saltwater influence even if only as a series of minor creeks. Control will be most successful if focused locally and on those areas where the natural pattern of change is progressing in a way considered unacceptable to the aesthetic, conservation and other values being applied to the area within the framework of an integrated management strategy.

The ecological, hydrological and sedimentary implications of intervention are still largely unpredictable and for that reason physical control of saltwater inundation should be kept to a minimum. Nevertheless, intervention may be required to protect high priority wetland resources as defined within the context of a conservation zoning strategy for wetland management. Two areas within which intervention is already required are: the western paleochannel and the extensive lower coastal plain with Melaleuca on the coastal plain; and the Shady Camp area, including the freshwater wetlands to the south of it.

The western paleochannel needs protection because it is low-lying, and saltwater, if it were to inundate, would rapidly penetrate upstream and possibly escape from the paleochannel itself, via paleocreeks on the plains, into the Melaleuca swamp to the west. The high conservation priority on this wetland justifies the continued effort to protect the area. Earthen barrages, as already constructed in this area, are probably the best means of protection.

The Shady Camp area presents a different problem. As described above, Shady Camp provides a convenient opportunity to limit the upstream penetration of saltwater because the channel is flanked by a broad and high levée on one side and upland on the other, it uses a natural rock bar as its substrate, and it is readily accessible for
maintenance. Saltwater is clearly attempting to reinvade further upstream and the Shady Camp Barrage currently provides a clear delimitation to the saltwater and freshwater interface. However, there are two ways (other than a breach in the Barrage) by which saltwater could get beyond this limit. Creeks to the north-west of Shady Camp could scour out in a Wet season and cut back past the barrage, or saltwater could penetrate through one of the other paleochannels, perhaps by elongation of the creek in the Red Lily Lagoon paleochannel. Both of these alternatives would make it considerably more difficult to exclude saltwater from the plains to the south of Shady Camp.

Gauging of Wet season flow over the Shady Camp Barrage, and across the plains between Alligator Head and Shady Camp (as was done in 1957 and in 1993 by Water Resources Division) should be continued to establish the effect of the Barrage. If Wet season scour is found to be a problem at Shady Camp, or if Wet season flows are found to overtop the levée banks because of the Barrage, then it might be appropriate to install a system of floodgates into the Barrage. In this case engineering advice should be sought. Ensuring that these creeks do not cut around the Barrage and that the creek in Red Lily Lagoon does not extend further south remains essential in order to keep saltwater out of the plains south of Shady Camp (Plate 18).

Earthen barrages have been successful in many cases in retarding saltwater intrusion. Further blocks should remain the preferred physical option where defined management priorities require that some action is taken to intervene in the penetration of saltwater inland. The present design appears to have been adequate in a number of instances (Sterling 1992). Excavations for block construction should be shallow, in order to prevent the release of very acidic and aluminium-rich waters, causing either local fish kills, or stressing vegetation, either natural or planted as part of the barrage and protection works.

Barrages and blocks generally retain floodwater on the plains longer than it would otherwise remain. If monitoring and research demonstrates that the changes are detrimental to magpie goose breeding, barramundi migration, or some other ecological factor, it may be necessary to revise the design further. Water levels could be controlled by the height of barrages, or by a system of floodgates or flapgates. Engineering advice should be sought in the design of major structures. However, the design may be less difficult than establishing which pattern of flooding and retention is the most ecologically sound. Where possible, engineering solutions should seek to replicate the processes and dynamics of the natural system, and should merge into the landscape, rather than contrast with it.

5.8.2. Monitoring

There is a need to continue to monitor the nature, rate and direction of changes to these plains. The present database of aerial photographs and satellite imagery should be regularly updated so that management decisions are based on current information. Aerial photography is probably the single most valuable monitoring tool, and aerial photographic coverage every second year is desirable. Further monitoring of the rates
and processes of tidal creek incision is required. This should consist of resurvey of cross-sections on expanding tidal creeks, maintenance of a photographic record of changes from photographic points on the plains, and monitoring of flows and sediment movements in a minor, expanding creek.

Monitoring water levels in the channels and on the plains is important, in relation to present and proposed landuses, and in terms of understanding the ecology of the plains, and the nature of environmental change. The water level recorders at Mount Bundey and Shady Camp should be maintained. Further records would also be valuable from other sites. A tide gauge within van Diemen Gulf would provide a record of tidal fluctuations in the gulf, and allow calibration on hydrodynamic modelling in the system and assist with more local tidal information on tidal delays and the accessibility of tidal creek networks at particular stages of the tide.

Understanding the hydrodynamics of fluviotidal flows is particularly important, especially if major intervention is anticipated. Collaborative work with the Water Resources Division should remain a high priority. The program should involve siting temporary water level recorders and recording observations on an actively eroding tributary. An automated weather station may be justifiable within the area, to provide up-to-date and site-specific data for research and monitoring. Further investigations need to be carried out on sediment transport patterns and channel bank stability.

Understanding of the plains would be increased by the application of a hydrodynamic model to water flows. Modelling is not simply a useful analytical tool, but increasingly is being recognised as a valuable approach to management and decision-making. A successful hydrodynamic model offers scope to simulate the effect of the construction of dams and barrages on the Lower Mary River plains, as well as possible responses to incremental sea level rise.

Preliminary data which might be used to begin calibration of a model have been processed by Water Resources Division, but the model being used does not adequately describe behaviour of the tidal network (D Williams, pers. comm., 1993). More sophisticated models are available commercially, some of which have the capacity and flexibility to incorporate tidal tributaries and fluvial components as well as catering for the inclusion of management structures such as barrages. Modelling will become particularly important if the more major physical options are ever considered.

While modelling allows insights into the possible behaviour of the system which might not otherwise have been expected, the Mary River is a unique system, evolving at a rapid rate, and it cannot be overemphasised that the only way to adequately understand all aspects of the system will be to continue to monitor it.

Survey data represent an important resource, not only in the designation of priorities for management, but also in ecological research and in the construction of any physical works. One of the highest priorities must be to determine heights on the paleoestuarine plain, particularly in the network of paleochannels, lower floodplain and backwater swamps just south of Shady Camp. This is particularly important because it will establish the vulnerability of the floodplains to saline intrusion should
saltwater penetrate beyond the Barrage. Additional surveying elsewhere on the plains, supplementing that already available, will be important in defining the vulnerability of other areas. In view of the large effort involved in surveying, often in arduous conditions, it is essential that good records be kept, and that survey marks are well-maintained on the plains. These will continue to be important, whether in the installation of structures or in the determination of whether a particular site will be suitable for magpie goose breeding. Where blocks are installed, they should be surveyed, with heights related to a local benchmark, and with subsequent observations to monitor compaction of the structure, erosion, and the success of vegetation establishment.

There is abundant evidence for the adverse impact that feral animals have had on these delicately balanced wetland systems. Degradation through the trampling, and swim-channel formation by buffalo is widely apparent, occasionally influencing the course that saltwater has taken in the expanding creek network. Eradication of feral buffalo means that this kind of damage is no longer being inflicted, but there remains a legacy from damage sustained in the past. Particular care needs to be taken to ensure that domesticated buffalo, and other stock, are not impacting the wetlands in an unacceptable way. It seems possible to manage freshwater wetlands for Dry season pasture, and to allow Wet season breeding populations of birds (Whitehead et al 1992). However, strict grazing management strategies and stocking densities will need to be observed and monitored over the plains, and zoning should designate areas which should be unavailable to stock.

It will be important to monitor the impact of recreational and tourist activities. Access, particularly 4WD access, but also boat and airboat access, should be monitored to establish its impact, and if necessary areas should be zoned for only limited access. Some parts of the plains, particularly the levées, may prove especially vulnerable to degradation by 4WD, as they have been in the past to buffalo impact. Riparian vegetation represents an important resource, and its damage, or the damage of fragile river banks, by unrestricted boat launching will need to be monitored, and controlled if necessary.

5.8.3. Research

There is a need for further research on the ecological resources of the Mary River wetlands and their interrelationships with physical factors. The research that has been carried out serves to emphasise the interconnectedness of ecological and physical processes, and the uncertainty of the implications of natural change and the impacts of intervention. In particular, the relative contribution of tidal and freshwater wetland resources, particularly fish stocks, crabs, saltwater crocodiles, and other resources which have commercial or recreational value, needs to be better understood. Assessment of the relative roles and importance of tidal and freshwater wetlands in terms of barramundi and bird populations also needs to be based on a sound evaluation.
Further geomorphological research is needed to clarify the Holocene and recent pattern of development in greater detail. Priority areas to expand the research findings arising from the present study include: the dating of more chenier ridges to refine the pattern of late Holocene coastal progradation; additional coring and dating of paleochannel sediments to further substantiate the pattern of paleochannel switching; and seismic stratigraphy and vibrocore surveys in van Diemen Gulf to establish the nature of the offshore source of sediment and to calculate more accurate sediment budgets for the system.

Further research on vegetation should concentrate on the natural pattern of succession from freshwater to saltwater vegetation. This would involve monitoring the establishment of mangroves and other halophytes, and the assessment of the effectiveness of mangroves in protecting erosional river banks. Vegetation research also needs to examine the success of planting to stabilise barrages. Again mangroves might be a suitable vegetation type to encourage, in order to encourage and accelerate the natural healing of the system.

A better understanding of the sub-surface hydrology of the plains is required. Some work, especially on deeper flows has begun, with the installation of piezometers (Jonauskas & Sterling, unpub), and with drilling by the Groundwater Assessment Section of the Water Resources Division (Jolly & Chin 1992). Water tables drop to around AHD (1–2 m below plains surface), and this explains natural oxidation of the sediments. Relatively little is known about lateral movement, perched water tables, and the diffusion of salts from the shallowly buried saline muds. Such information will be useful in terms of managing potential acid sulphate soils, enhancing the ecology of the region, and managing any pollutants that may be released into the system.
GLOSSARY

Abstraction
Elimination or deduction of tidal creeks from a network through infill.

Accretion
Gradual build up or accumulation of sediment over time. Vertical accretion is the
dominant process of sedimentation over near-horizontal plains surfaces, but on a
shelving coast sedimentation is more likely to occur as lateral accretion (ie, as
build-out or progradation of the coast).

Avulsion
Sudden switching or changing of a river course, leaving the former course
unoccupied.

Backwater swamp
A low-lying wetland area, not directly connected to a river or tidal channel, but
subject to flooding. Often at the margin of the plains within a re-entrant.

Beach ridge
A low continuous ridge of sandy beach material formed behind a beach by the
action of waves and currents and lying more or less parallel to the shoreline.

Bioturbation
The disturbance of sediments by the activities of plants, or more usually animals,
especially invertebrates.

Chenier
A continuous or discontinuous narrow sandy/shelly ridge, usually parallel to the
shore, deposited by storm waves upon a plain of fine grained coastal sediments,
usually muds.

Cumec
A measure of volume flow, equal to one cubic metre per second.

Dendritic
Branched like a tree; a pattern of natural stream courses in which channels branch
irregularly in all directions and at any angle.

Elaboration
A process of tidal creek network expansion by which additional tributary creeks
are added within the area defined as the former network.

Elongation
A process of tidal creek network expansion by which individual creeks grow or
extend further upstream.
Fandelta
A low, gently sloping cone-shaped mass of alluvial sediment which accumulates where fluvial sediments have splayed out from their course over more coastal sediments.

Flap gate
A hinged gate, usually opening in only one direction, which excludes water at high tide and allows drainage at low tide.

Flocculation
The aggregation of fine sediments (usually clays) into larger particles through chemical attractions between grains. A process often accentuated in saline water.

Floodplain
A relatively flat area bordering a river which becomes submerged during floods, at which time further sediment may be added to the plains surface.

Halophyte
A plant which lives in and can tolerate a salty environment.

Holocene
The last 10,000 years; the most recent epoch of the Quaternary period.

Hydraulic radius
A ratio determined by the cross-sectional area of a channel divided by the wetted perimeter.

Hydrodynamics
The study of fluid motion and fluid-boundary interaction.

Isochrons
Lines that connect points of equal time, in this case time of deposition.

Levée
A naturally formed bank of higher ground occurring adjacent to a river and deposited by flood waters. Artificially constructed banks which contain floodwaters are also referred to as levées.

Mangrove facies
Facies is a term for a unit of sediment deposited under a particular set of environmental conditions. Mangrove facies is characteristically mud deposited beneath mangrove forests.

Mean sea level
The average of elevation of the sea surface over a 19 year period. In this study the Australian Height Datum (AHD) is presumed to be very close to mean sea level (MSL).
Mean tide level
   The reference plane halfway between high water and mean low water. Channel
genometry will modify the fluctuation of water level as it moves upstream over the
tidal cycle, such that the mean tide level is unlikely to correspond with mean sea
level further downstream or in the open sea.

Midden
   A mound of refuse indicating some prehistoric occupation or camping site,
generally containing shells, bones and/or artefacts.

Mud
   In sedimentological terms, mud is a sediment composed predominantly of silt
and/or clay-sized particles (<63 microns or 0.063 mm diameter). In most cases
these sediments comprise both silt and clay and as they are not readily
distinguishable in the field, the term 'mud' has been used throughout this study.

Oclusion
   Cut-off or closure, in this case closure or damming of the river outlet to the sea.

Paleochannel
   A remnant stream channel that has been completely or partly infilled by younger
sediments.

Paleocreek
   A remnant creek that has been infilled by younger sediments. A paleocreek is
usually an identifiable tributary of a paleochannel.

Paleoestuarine
   A formerly estuarine area. In this study, the term paleoestuarine plain is used to
describe that area of the plains which stratigraphic studies have indicated were
formed initially under estuarine conditions but which no longer experience tidal or
marine influences.

Point bar
   A low curved ridge or shoal of sand or sandy mud that forms on the convex bank
of a river meander.

Pollen analysis
   The study of pollen grains within sediment samples to reconstruct the relative
proportions of different plant taxa in past vegetation as an indicator of previous
environmental conditions.

Pollen diagram
   A diagram illustrating the relative proportions at various depths through a core of
different plant pollen types.

Pollen spectra
   A representation of the varying proportions of different plant pollen types in a
sample.
Progradation
The gradual seaward build-out of the coast, through accretion or deposition of sediment.

Provenance
The source of sediment.

Radiocarbon dating
A method of dating the time of death of fossil wood or shell, based on the amount of the radioactive carbon isotope C\textsuperscript{14} remaining as a consequence of radioactive decay in relation to stable carbon isotopes which do not decay.

Re-entrant
An inlet or embayment; in this case an embayment within the upland margin of the plains usually occupied by backwater swamp.

Regressive
Indicating a marine regression; sediments indicate that the influence of the sea has decreased at a site either because the sea has fallen or because sediment has built up (an offlap sequence).

Rhizophoraceous
Mangroves of the family Rhizophoraceae, including Rhizophora, Bruguiera and Ceriops.

Saltwater intrusion
The penetration of saltwater into previously freshwater environments.

Tidal asymmetry
A situation where the pattern of water level rise or fall and current velocity is significantly different on the flood from that on the ebb tide of the tidal cycle. Such differences are important because they can result in significant net movements of sediment either upstream or downstream.

Tidal influence
A fluctuation of water level induced by tidal factors but not necessarily involving saline water.

Tidal prism
The total volume of water which flows into a tidal basin with a flood tide and then out again with the ebb. It can be envisaged as the difference between an embayment's (or tidal creek's) mean high-water volume and its mean low-water volume.

Transgressive
Indicating a marine transgression; sediments indicate that the sea has invaded an area of previously dry land (an onlap sequence).
REFERENCES


References 131


Kershaw AP, 1983. The vegetation record from north east Australia, 7 ± 2 Ka, in Chappell J & Grindrod A (eds), Proceedings of the 1st CLIMANZ Conference, Department of Biogeography & Geomorphology, Australian National University, Canberra, 100–1.


## APPENDIX

### Key to core logs

<table>
<thead>
<tr>
<th>Sediment texture</th>
<th>Sediment structure and composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>Laminated</td>
</tr>
<tr>
<td>Gravel and sand</td>
<td>Finely laminated</td>
</tr>
<tr>
<td>Sand</td>
<td>faintly laminated</td>
</tr>
<tr>
<td>Muddy sand</td>
<td>Organic top soil</td>
</tr>
<tr>
<td>Fine sand/silt</td>
<td>Shell hash</td>
</tr>
<tr>
<td>Sandy mud</td>
<td>Oxidised</td>
</tr>
<tr>
<td>Mud</td>
<td>Cracked</td>
</tr>
<tr>
<td>Clay</td>
<td>Bioturbated</td>
</tr>
</tbody>
</table>

Wood fragments
Organic fragments
Disseminated organic flecks
Shell
Ferruginous nodules
Carbonate nodules
### Drift Core No. 26

**Date:** 27 Sep 1989  
**Location:** Offshore Surtchon Arm, western margin of Mary River Basin

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Top of core: light grey, clayey, organically enriched clay.</td>
</tr>
<tr>
<td>60</td>
<td>Dark grey clay with orange-weathered streaks.</td>
</tr>
<tr>
<td>80</td>
<td>Pale grey to orange-weathered clay.</td>
</tr>
<tr>
<td>100</td>
<td>Orange-brown clay, black (possibly organics).</td>
</tr>
<tr>
<td>120</td>
<td>White clay, sandy, some marine fossils.</td>
</tr>
<tr>
<td>150</td>
<td>White sandy clay, with orange-weathered streaks.</td>
</tr>
<tr>
<td>200</td>
<td>White sandy clay, grading to sandy grey.</td>
</tr>
<tr>
<td>250</td>
<td>Wood and marine shell fragments.</td>
</tr>
</tbody>
</table>

### Drift Core No. 27

**Date:** 27 Sep 1989  
**Location:** Offshore Surtchon Arm, western margin of Mary River Basin

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Dark grey clay, organically enriched.</td>
</tr>
<tr>
<td>40</td>
<td>Mud on dark grey clay with occasional white flecks, possibly carbonates.</td>
</tr>
<tr>
<td>80</td>
<td>Organic material and shell fragments.</td>
</tr>
<tr>
<td>140</td>
<td>Organic material and shell fragments.</td>
</tr>
<tr>
<td>160</td>
<td>Orange-brown clay, white pieces of shell.</td>
</tr>
<tr>
<td>170</td>
<td>White sand, with occasional marine fossils.</td>
</tr>
<tr>
<td>220</td>
<td>White sand, with occasional marine fossils.</td>
</tr>
<tr>
<td>240</td>
<td>Organic material and shell fragments.</td>
</tr>
<tr>
<td>340</td>
<td>Blush grey sand with woody fragments.</td>
</tr>
</tbody>
</table>

### Drift Core No. 28

**Date:** 27 Sep 1989  
**Location:** Offshore Surtchon Arm, western margin of Mary River Basin

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Dark grey clay, organically enriched.</td>
</tr>
<tr>
<td>20</td>
<td>Dark grey clay, black (possibly organics).</td>
</tr>
<tr>
<td>50</td>
<td>Orange-brown clay, black (possibly organics).</td>
</tr>
<tr>
<td>60</td>
<td>Pale grey to orange-weathered clay.</td>
</tr>
<tr>
<td>80</td>
<td>Sandy clay.</td>
</tr>
<tr>
<td>100</td>
<td>Orange-brown clay, some marine fossils.</td>
</tr>
<tr>
<td>140</td>
<td>Orange-brown clay, some black and orange fossils.</td>
</tr>
<tr>
<td>200</td>
<td>Blush grey sand with orange nodules.</td>
</tr>
<tr>
<td>225</td>
<td>Piece of wood.</td>
</tr>
</tbody>
</table>

---

**Note:** The descriptions include a variety of sediment types, from clay and sandy clay to wood and marine shell fragments, indicating a rich and diverse assemblage of materials. The cores provide valuable information about the geological history and environmental conditions of the Mary River Basin.
<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Surface 3 cm, Sedge, herb, and stem leaf fragments in sand clay, 1:0 Bm.</td>
</tr>
<tr>
<td>53</td>
<td>Black sand clay, 1:0 Bm.</td>
</tr>
<tr>
<td>82</td>
<td>Mixed with 60% fine black to grey clay, 1:00 Bm.</td>
</tr>
<tr>
<td>130</td>
<td>Black grey clay, orange to brown.</td>
</tr>
<tr>
<td>150</td>
<td>Black grey clay, very orange.</td>
</tr>
<tr>
<td>190</td>
<td>Black grey clay with the edges of the clay, very orange.</td>
</tr>
<tr>
<td>230</td>
<td>Black grey clay with the edges of the clay, very orange with some small clay fragments.</td>
</tr>
<tr>
<td>250</td>
<td>Mixed with clay.</td>
</tr>
<tr>
<td>295</td>
<td>Mixed with clay.</td>
</tr>
<tr>
<td>320</td>
<td>Mixed with clay.</td>
</tr>
<tr>
<td>340</td>
<td>Mixed with clay and root fragments.</td>
</tr>
<tr>
<td>345</td>
<td>Mixed with roots, roots and root fragments.</td>
</tr>
<tr>
<td>370</td>
<td>Mixed with organic roots and root fragments.</td>
</tr>
<tr>
<td>390</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>400</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>450</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>500</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>550</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>600</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>650</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>700</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>750</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>800</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>850</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>900</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>950</td>
<td>Organic roots and root fragments.</td>
</tr>
<tr>
<td>1000</td>
<td>Mixed with sedge, root fragments, and root fragments.</td>
</tr>
</tbody>
</table>
### Drill Core G.R. (Ref 277)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>Dry, coarse clay, heavily bioturbated by bird eggs, dark gray clay, organically enriched (0-45cm)</td>
</tr>
<tr>
<td>10-20</td>
<td>Brush gray clay with oxidation and organic matter</td>
</tr>
<tr>
<td>20-80</td>
<td>Dark gray clay, abundant organic matter (120-130cm)</td>
</tr>
<tr>
<td>80-120</td>
<td>Essentially oxidized between 140-150cm</td>
</tr>
<tr>
<td>120-150</td>
<td>Several orange tuffs and streaks, decrease in oxidation below 150cm</td>
</tr>
<tr>
<td>150-200</td>
<td>Abundant organic fragments</td>
</tr>
<tr>
<td>200-220</td>
<td>Pale brown sandy clay, wood fragments at 200cm</td>
</tr>
<tr>
<td>220-270</td>
<td>Brush gray clay (215-250cm), slightly oxidized (25cm)</td>
</tr>
<tr>
<td>270-350</td>
<td>Pale yellow sandstone (270-350cm), fine sand with growth lines of parallel clay (&lt;0.5cm thick)</td>
</tr>
<tr>
<td>350-300</td>
<td>Interstratified with lenses of disseminated organics</td>
</tr>
<tr>
<td>300-320</td>
<td>Disseminated organics and oxidized charcoal</td>
</tr>
<tr>
<td>320-400</td>
<td>Dark brown clay with pale brown horizontal laminae</td>
</tr>
<tr>
<td>400-450</td>
<td>Occasional thin lenses of disseminated organics and oxidized charcoal (300-450cm)</td>
</tr>
<tr>
<td>450-500</td>
<td>Dark brown clay, essentially organic sand at 450cm</td>
</tr>
</tbody>
</table>

### Drill Core G.R. (Ref 277)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>Dry, cracked surface with Myriophyllum alternantha, dark grey clay, organically enriched (10-60cm)</td>
</tr>
<tr>
<td>10-55</td>
<td>Brush dark grey clay</td>
</tr>
<tr>
<td>55-100</td>
<td>Brownish clay with orange tuffs and occasional organics, pale brown silty laminae (100cm)</td>
</tr>
<tr>
<td>100-150</td>
<td>Oxidation in oxidized disseminated organics</td>
</tr>
<tr>
<td>150-200</td>
<td>Brush brown silty clay with slight oxidation</td>
</tr>
<tr>
<td>200-250</td>
<td>Brush brown sandy clay</td>
</tr>
<tr>
<td>250-300</td>
<td>Minor organic fragments, possible laminations</td>
</tr>
<tr>
<td>300-350</td>
<td>Occasional grey sand pockets</td>
</tr>
<tr>
<td>350-400</td>
<td>Shell organic fragments, otherwise homogenous</td>
</tr>
<tr>
<td>400-450</td>
<td>Transition into grey mud with organics</td>
</tr>
<tr>
<td>450-500</td>
<td>Brush grey clay with disseminated organics</td>
</tr>
<tr>
<td>500-550</td>
<td>Dark grey silty clay, organics</td>
</tr>
<tr>
<td>550-600</td>
<td>Yellowish grey silty clay, oxides</td>
</tr>
<tr>
<td>600-650</td>
<td>Brush grey silty clay, no organics</td>
</tr>
<tr>
<td>650-700</td>
<td>Brush grey silty clay with occasional pockets of pale, grey sand sized aggregates along which the clay splits</td>
</tr>
<tr>
<td>700-750</td>
<td>Dry grey silty clay, no shells or organics</td>
</tr>
<tr>
<td>750-800</td>
<td>Brush grey silty clay</td>
</tr>
<tr>
<td>800-850</td>
<td>Increasingly sandy</td>
</tr>
<tr>
<td>850-900</td>
<td>Yellowish grey calcareous sand with minor ironstone</td>
</tr>
<tr>
<td>900-950</td>
<td>Increasingly red with depth, no shells apparent</td>
</tr>
</tbody>
</table>

### Appendix 147

Drillhole location: Upper coastal plain - 4km NNE of Shady Camp, 13km south of Townsville. Under a mangrove forest, but adjacent to a floodplain.
<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Dry, cracked surface of dark grey clay, organically enriched</td>
</tr>
<tr>
<td>65</td>
<td>Dark grey clay (siltstone matrix)</td>
</tr>
<tr>
<td>100</td>
<td>Pale brown-grey clay, orange and brown streaks</td>
</tr>
<tr>
<td>130</td>
<td>Pale brown-grey clay with dark organic streaks, oxidation horizons, minor sand lenses, organically enriched</td>
</tr>
<tr>
<td>180</td>
<td>Dark grey slightly sandy clay, decreasing oxidation, black organic streaks</td>
</tr>
<tr>
<td>200</td>
<td>Time of oxidation up to 130 cm, woody fragments at 236 cm</td>
</tr>
<tr>
<td>250</td>
<td>Dark grey clay with abundant disseminated organic matter, orange oxidation, 250-350 cm</td>
</tr>
<tr>
<td>300</td>
<td>Bluish grey clay with minor pale yellow sandy patches</td>
</tr>
<tr>
<td>330</td>
<td>Minor disseminated organic horizons throughout as above, but less organic, sandy horizontal laminations at 360-390 and 395 cm</td>
</tr>
<tr>
<td>400</td>
<td>White breaks and pink laminations</td>
</tr>
<tr>
<td>450</td>
<td>Abundant shell fragments at 435 and 440 cm</td>
</tr>
<tr>
<td>500</td>
<td>Pale brown-grey clay with sparse organic, desiccated coarse sand laminations at 425 and 450 cm</td>
</tr>
<tr>
<td>550</td>
<td>Minor sand laminations at 485 and 495 cm</td>
</tr>
<tr>
<td>590</td>
<td>Black-grey brecciated clay</td>
</tr>
<tr>
<td>620</td>
<td>Black sand and shell hash at 620 and 625 cm</td>
</tr>
<tr>
<td>650</td>
<td>Minor sand and shell hash at 650 cm</td>
</tr>
<tr>
<td>700</td>
<td>Black sand and shell hash at 665, 670 and 675 cm</td>
</tr>
<tr>
<td>750</td>
<td>Nirghinous black-grey sand clay</td>
</tr>
<tr>
<td>800</td>
<td>Black and shell hash at 720 cm</td>
</tr>
<tr>
<td>850</td>
<td>Dark grey sandy clay with abundant shells, major sand laminae at 763-765 cm</td>
</tr>
<tr>
<td>880</td>
<td>Very dark grey clay, minor sand laminae at 860-865 cm, woody fragments at 880 cm, orange shell hash at 895 cm</td>
</tr>
<tr>
<td>900</td>
<td>Dark grey clay with occasional charcoal and manganiferous horizons, occasional sand laminae, no shell occurring due to difficulties with core recovery</td>
</tr>
<tr>
<td>970</td>
<td>Light grey sandy clay, with trace carbonate nodules</td>
</tr>
<tr>
<td>1000</td>
<td>Yellow clay with red and orange horizons</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Dry, cracked clay</td>
</tr>
<tr>
<td>85</td>
<td>Dark grey clay, organically enriched (5-80 cm)</td>
</tr>
<tr>
<td>100</td>
<td>Dark grey clay with oxidation and organic horizons</td>
</tr>
<tr>
<td>120</td>
<td>Bluish grey clay with very orange horizons and streaks</td>
</tr>
<tr>
<td>170</td>
<td>Brownish grey clay with orange horizons and organic matter</td>
</tr>
<tr>
<td>200</td>
<td>Bluish grey clay with brown and orange mottling and disseminated organic streaks</td>
</tr>
<tr>
<td>260</td>
<td>Line of oxidation</td>
</tr>
<tr>
<td>300</td>
<td>Bluish grey clay with organic fragments</td>
</tr>
<tr>
<td>350</td>
<td>Bluish grey clay with organic fragments and trace shell</td>
</tr>
<tr>
<td>360</td>
<td>Bluish grey clay with minor shell and organic fragments</td>
</tr>
<tr>
<td>450</td>
<td>Bluish grey clay with minor shells and shell fragments</td>
</tr>
<tr>
<td>470</td>
<td>Bluish grey clay with abundant shell fragments and minor disseminated organic matter</td>
</tr>
<tr>
<td>490</td>
<td>Transition to bluish-grey clay with abundant shells, distinct and lenticular with numerous large white breaks</td>
</tr>
<tr>
<td>510</td>
<td>Sandy clay with very fine shell hash</td>
</tr>
<tr>
<td>530</td>
<td>Sandy clay with large shells including Turr噫Edial</td>
</tr>
<tr>
<td>580</td>
<td>End of shell hash, light clay with manganese fragments</td>
</tr>
<tr>
<td>650</td>
<td>Bluish-grey clay with abundant organic fragments</td>
</tr>
<tr>
<td>630</td>
<td>Bluish-grey clay with large shell fragments</td>
</tr>
<tr>
<td>650</td>
<td>Bluish-grey clay with abundant charcoal pieces</td>
</tr>
<tr>
<td>670</td>
<td>Bluish-grey clay, organically enriched</td>
</tr>
<tr>
<td>700</td>
<td>Blue-grey slightly sandy clay with minor shell fragments</td>
</tr>
<tr>
<td>750</td>
<td>Bluish-grey clay with abundant organic fragments</td>
</tr>
<tr>
<td>760</td>
<td>As above with minor shell fragments</td>
</tr>
<tr>
<td>800</td>
<td>Bleaching of organic matter</td>
</tr>
<tr>
<td>850</td>
<td>Bluish-grey clay with abundant charcoal, white shells and shell fragments, sulphides</td>
</tr>
<tr>
<td>900</td>
<td>Bluish-grey slightly sandy clay with abundant charcoal</td>
</tr>
<tr>
<td>930</td>
<td>Transition to sand, dark grey clay</td>
</tr>
<tr>
<td>950</td>
<td>Sandy dark grey clay, abundant woody fragments, sulphides</td>
</tr>
<tr>
<td>970</td>
<td>Sandy dark grey clay, abundant woody fragments, sulphides</td>
</tr>
</tbody>
</table>

**Note:** The table provides a detailed description of the core samples, including the depth, color, and characteristics of each layer, helping to understand the geological composition and changes over time.
<table>
<thead>
<tr>
<th>CM</th>
<th>Depth</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Clayey surface of dark grey clay organically enriched</td>
</tr>
<tr>
<td>45</td>
<td>pale brownish grey clay with orange and black streaks</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>pale brownish grey clay with orange mottles and occasional disseminated organic streaks</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>blue-grey clay, 4 cm band of carbonization</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>organic fragments, bent of oxidation</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>brush grey clay with minor organic fragments</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>abundant woody fragments</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>brush grey clay with minor organic fragments (560-2000 cm)</td>
<td></td>
</tr>
<tr>
<td>330</td>
<td>large carbonate nodules at 320 and 3330 cm</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>brush grey clay with abundant organic fragments</td>
<td></td>
</tr>
<tr>
<td>450</td>
<td>woody fragments at 450 cm, otherwise featureless clay</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>brush grey clay, occasional disseminated and organic fragments</td>
<td></td>
</tr>
<tr>
<td>550</td>
<td>minor organic fragments</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>brush grey clay</td>
<td></td>
</tr>
<tr>
<td>650</td>
<td>minor shell fragment</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>no significant woody fragments between 500-700 cm</td>
<td></td>
</tr>
<tr>
<td>720</td>
<td>brush grey clay sandy clay</td>
<td></td>
</tr>
<tr>
<td>730</td>
<td>dark grey sand</td>
<td></td>
</tr>
<tr>
<td>780</td>
<td>pale blue sand and minor clay</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>pale blue sand and clay</td>
<td></td>
</tr>
</tbody>
</table>