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DISTURBANCE TO MANGROVES IN TROPICAL-ARID WESTERN AUSTRALIA: HYPERSALINITY AND RESTRICTED TIDAL EXCHANGE AS FACTORS LEADING TO MORTALITY

Environmental Protection Authority
Perth, Western Australia
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DISTURBANCE TO MANGROVES IN TROPICAL -ARID WESTERN AUSTRALIA : HYPERSALINITY AND RESTRICTED TIDAL EXCHANGE AS FACTORS LEADING TO MORTALITY

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ii. SUMMARY

1. Sources and extent of disturbances to mangroves are described for the arid Dampier-Cossack region of the Pilbara,Western Australia.

2. Over 16% of the 70km^2 of mangals occurring from Cape Preston to Cape Lambert are now dead. *Avicennia marina* makes up 87% of living mangroves in the region.

3. Greatest mortality of mangroves has occurred from permanent ponding of seawater during construction of brine ponds for a salt evaporator close to Dampier.

4. Other sites with mangroves suffering widespread mortality are landward-located, in hypersaline soils and with disturbance to natural tidal exchange.

5. Disturbances to mangroves are related to urban and industrial development and include examples of altered tidal exchange, removal of mangroves, dumping of dredge spoil and bunding.

6. Comparisons of tidal exchange and soil properties on each side of a road truncating a mangal implicate two factors in decline and death of the mangroves landward of the road, and these have their greatest impact at different times of the year.

   - Reduced frequency and duration of seawater recharge, around the time of the winter solstice, which increases salinity.
   - Retention of seawater, around the time of the equinoxes, which extends the duration of inundation and submergence of breathing roots from hours to days.

7. Living mangroves in this region are typically associated with groundwater salinities below 90 $^0/00$.

8. Changes in soil properties measured over a tide cycle reveal that during the absence of seawater recharge soil salinity increases to very high values at the surface but rapidly re-establishes lower values with the return of tidal wetting. Further down the soil profile salinity and moisture remain relatively stable irrespective of tidal wetting or drying. Changes in chloride mirror those of salinity over the tide cycle and constitute about 70% of TDS.

9. The water table is shallow, being at the surface during inundation and within 10 cm of the surface between inundations during the wetting phase of the tide. In the absence of recharge this falls an average 7 cm d^{-1}.

10. Groundwater salinity is diluted for short intervals (hours) during tidal inundation in shallow bioturbated soils but rapidly re-establishes higher salt concentrations following inundation.

11. Salinity of groundwater under salt flats landward of the main vegetation zone is hypersaline, spatially-variable and temporally-stable; changes in salinity between successive tidal wettings are small and are apparently not strongly influenced by inundating seawater.

12. There were differences in soil properties on each side of a road restricting tidal exchange. Over the same tide cycle salinity was elevated by an average 26 $^0/00$, up to a maximum 41 $^0/00$, at the depths of the cable roots under the remaining living trees in the tidally-restricted mangal, compared with healthy trees in the adjacent unrestricted site. Soils in the tidally-restricted mangal also displayed a lower silt and higher clay fraction.

13. Soil properties were measured at the extreme seaward and landward margins of the dead zone of mangroves in the tidally-restricted mangal and compared with those separated by the road in the adjacent, healthy tidally-unrestricted mangal. This suggests that soil salinity has been increased by about 20 $^{0}/00$ under the remaining living trees close to the road and by about 50 $^{0}/00$ at the extreme landward limit of the original, but now-dead, mangroves.

14. Differences in soil properties on each side of the road at Cossack over a tide cycle suggests that tidal restriction introduced by this disturbance has had most impact on the trees through its role in increasing the salt content of the water supply rather than reducing the amount of water available externally to the roots.

15. Priority should be given to minimising changes to the natural exchange of seawater in the mangrove communities of this region in future planning and development schemes which impinge on these communities and modify their water supply. Localized disturbances which alter both the amount and type of water flow can have deleterious effects on the mangroves well removed from the original source of the disturbance.

1. INTRODUCTION

The mangroves of the arid Pilbara coast in north-west Australia are situated in a biogeographical region experiencing seasonally high temperatures and low annual rainfall (< 300 mm) associated with high evaporation (Gentilli 1972). Consequently the ratio of rainfall : evaporation, as a measure of the "coastal aridity index" (Hamilton & Snedaker 1984), is very low on this coastline (0.08 to 0.21; Figure 1). Factors which govern the survival of the mangroves may be expected to differ from those operating on mangroves in more humid, wetter climates such as occurs in north and north-east Australia. In this region mangals typically appear as a narrow belt of vegetation fringing the sea-shore and along the margins of tidal creeks, backed by well-developed salt flats and an extensive arid hinterland. They display a lower diversity of species compared with similar communities further north. Of the 17 mangrove species in Western Australia, represented in 15 genera (Semeniuk, Kenneally and Wilson 1978), only seven occur in the Pilbara region, dominated by the grey mangrove, *Avicennia marina*, and the stilt mangrove, *Rhizophora stylosa*. Trees are smaller here, with less-complex zonation than mangals further north, and typically form a scrubby woodland rarely over 4 or 5 m (Semeniuk, 1983). *Avicennia* grows as single or multi-stemmed upright or recumbent trees or shrubs, forming a closed woodland in the seaward zones of the mangals but grading to low, open scrub landward. One notable example of "stunted" growth here is the spurred mangrove, *Ceriops tagal*, which is commonly found as mature plants less than a metre tall in a landward associationwith *Avicennia marina* .

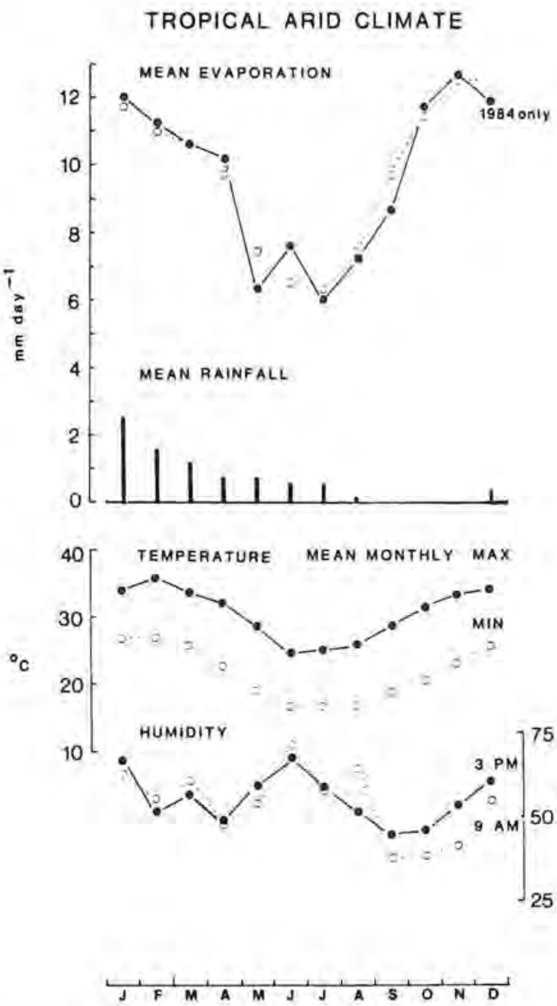


Figure 1. Seasonal changes in climatic factors in tropical-arid Western Australia. Figures shown are long-term means from different weather stations in the study area (see Figure 2 below): monthly rainfall (Cape Lambert; 1971-1985); monthly maximum and minimum air temperatures and mid-morning and mid-afternoon humidity (Cape Lambert; 1970-1985); monthly evaporation (Dampier Salt; 1972-1985). Data are from the Commonwealth Bureau of Meteorology.

The natural pressures faced by mangroves on this coast are likely to be considerable. The more obvious ones, in view of the climate, are a limited supply of water and associated high salinity. Any detrimental effects these natural "stressors" have on mangrove communities are likely to be aggravated by disturbances from urban and industrial expansion in a region where the water supply servicing coastal towns is met largely from groundwater (Brown, Harrison and Jacobson 1983). This development has already impinged to varying degrees on the mangals at Karratha, Dampier and Port Hedland, the most visible being a large salt evaporator close to Dampier and iron-ore exporting facilities located on the coast at Dampier, Cape Lambert and Port Hedland and linked by rail to ore deposits in the interior (Nicholson 1980; Chittleborough 1983). Isolation of mangroves during construction of brine ponds for the salt evaporator resulted in the death of an extensive area of these communities. The increased need for access to the coast has now opened further mangrove communities in the region to several other types of disturbance related to road and harbour construction, with resulting impact from dredge-spoil, altered drainage and bunding.

Mangals of the north-west coast are unique in Australia because they are the only examples of such coastal communities growing in a tropical-arid climate. Despite this, there have been no studies undertaken to measure the dynamics of these communities and to examine how the trees cope with their harsh environment. This paper is the first of several reporting results of field studies conducted between 1983 and 1985 to describe the disturbances associated with mangroves in this region, to quantify ranges of edaphic and atmospheric factors operating on the trees and to measure the physiological responses to daily and seasonal changes in some of these factors. The sites chosen for this study were largely confined to landward margins of the vegetation zones of the mangals where natural stressors such as reduced water supply and high salt concentrations are likely to have their greatest impact. A preliminary survey of mangrove communities in the Dampier and Cossack region suggested a link between the appearance of moribund or dead trees and excessive salt concentrations in the groundwater (Gordon 1983). Though the salinity ranges of groundwater and soils in mangrove communities of this region have been reported previously, particularly the spatial variability in relation to zonation (see Semeniuk 1983; 1985), there has been little information yet gathered on small-scale changes in soil properties in response to variable tidal recharge or how these are affected by man-induced perturbations. Attention has been given here to measuring changes in several soil properties under variable tidal recharge at landward locations in the mangals, including sites where road construction has introduced a disturbance to the natural exchange of seawater and there is associated with it widespread death of mangroves landward of the road. Differences in soil properties and tidal exchange in the mangal on each side of the road have been used to gauge the impact of this disturbance on the water supply around the trees and to provide background information for interpreting daily and seasonal patterns of water use and salt exchange by the trees (Gordon, in preparation).

2. MATERIALS and METHODS

2.1 LOCATION OF STUDY

The surveyed area includes the coastline and islands from Cape Preston to Cape Lambert (Figure 2). Mangals visited to assess disturbance are located around Dampier and at Cape Lambert, some 50 km further east (Figure 2). Sites used for measurements of salinity and tidal exchange are shown in Figure 3.

2.2 AREAS OF MANGAL

Maps of mangal distribution prepared for this region for the Environmental Protection Authority, Western Australia (unpublished) and colour and false-colour infra-red aerial photographs (Department of Lands Administration, Western Australia) were used to determine the extent of these communities. These were calculated from the above sources using an electronic digitized planimeter (Summagraphics Corp, Fairfield, Connecticut, USA).

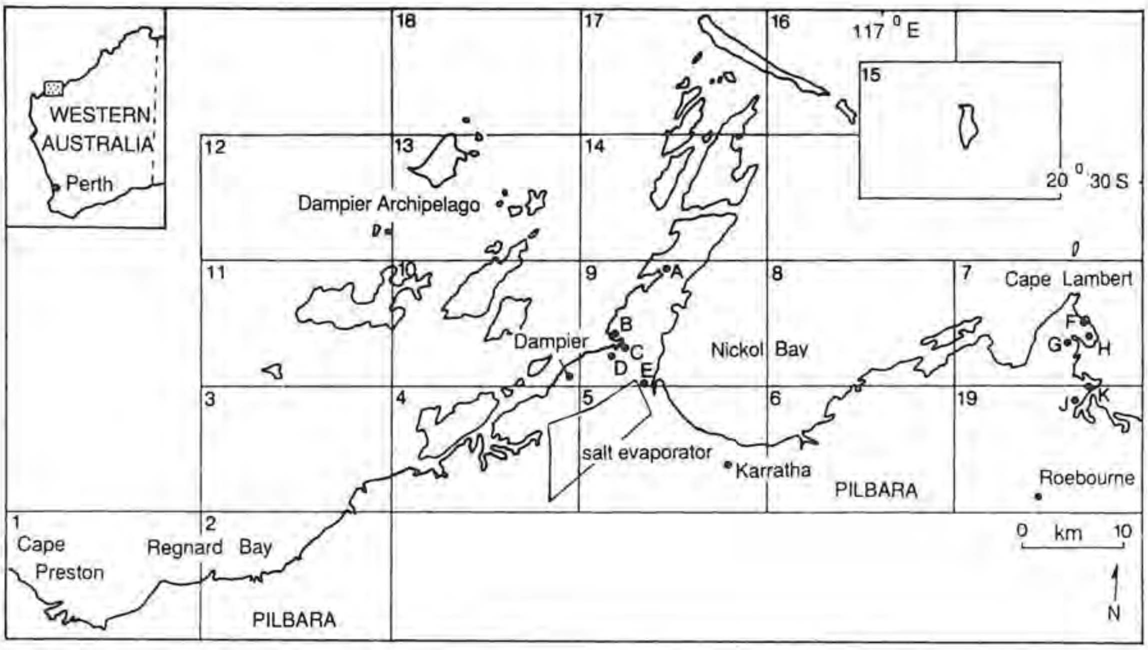


Figure 2. Location of study sites. Limits of the 19 maps used to calculate areas of mangals from Cape Preston to Cape Lambert are superimposed onto the map. Specific locations shown are A: Withnell Bay B: North-West Shelf Gas Project (NWSGP) Supply Base and Woodside Petroleum Pty Ltd. Spoil Area 4, at King Bay C: King Bay causeway D: south-west King Bay E: Levee 24, Dampier Salt Pty Ltd F: Sam's Creek G: Pope's Nose Creek H: John's Creek fishing harbour J: Cossack causeway K: Cossack township. Inset on left shows the location of the study area (stippled) on the Western Australian coast.

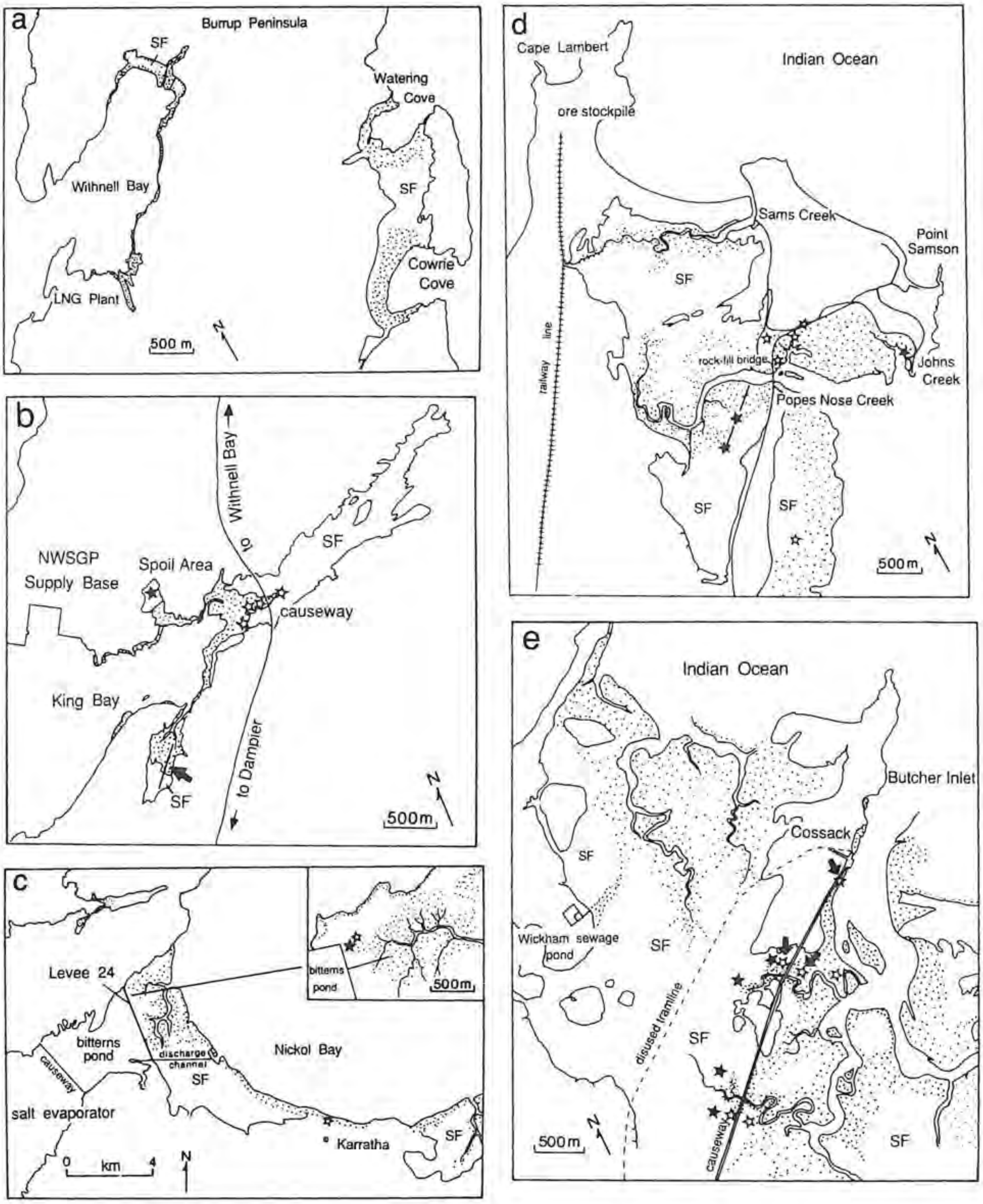
2.3 TIDAL EXCHANGE

The frequency and duration of tidal recharge was determined for landward sites at King Bay and Cossack using tables of predicted tide heights for the closest stations for which tide records exist, at Dampier and Port Walcott, respectively (Anonymous 1984; 1985). To assess the frequency and extent of tidal inundation, water penetration and its duration at each site during recharge was recorded and compared with the predicted figures.

A programmable electronic data logger (Wesdata, Western Australia) connected to a pressure transducer (R S Components Ltd, England) was used to measure the duration of tidal wetting and water depths experienced during inundation over successive tides during the spring equinox. The logger was pre-programmed in the laboratory, sealed in a water-tight jacket and buried in the mangrove soils with the pressure sensor located at ground level. Pressure changes were calibrated to water depth and logged continuously at 10-minute intervals over the tide cycle.

2.4 GROUNDWATER SAMPLING

Groundwater was obtained by excavating to free water. At King Bay sampling was performed either manually from pits or from permanently-seated PVC sampling pipes (length 1 m; O D 5 cm) placed at intervals across the salt flat and into the landward mangal. Each pipe was fitted with a conical tip inserted into one end, flush with the sides to aid placement into the soil. Water passed into the pipes through a series of 10 cm long vertical saw-cuts placed around the base. A set of these pipes was used to sample at different depths at one site, either manually between successive flood tides or at three hour intervals, over 2 to 3 days, by connecting the pipes to programmable, automatic water samplers (Model 1680, Instrumentation Specialities Company, Nebraska, USA). The pipes were sampled and drained automatically at a predetermined time and allowed to recharge for the required time by setting the machine to the desired sampling program. For manual readings, the pipes were first drained using a portable, manual vacuum pump then allowed to recharge. The pipes were capped between readings to exclude seawater entering during tidal submergence.



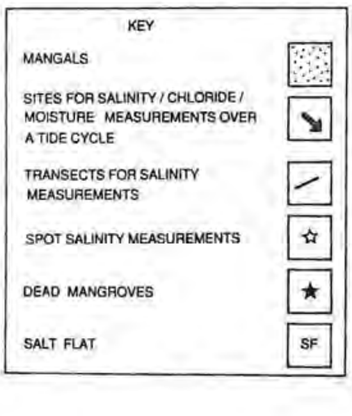


Figure 3. Locations of sites visited for salinity and tidal exchange measurements. a: Withnell Bay b: NWSGP Supply Base and mangals atKing Bay c: Dampier Salt Pty. Ltd. Levee 24 and mangals fringing Nickol Bay at Karratha d: Pope's Nose Creek, Sam's Creek and John's Creek fishing harbour e: Cossack and the causeway linking the town to the Roebourne-Pt Samson Road. Transects used for salinity measurements are shown to scale. Locations with mortality of mangroves and those used for spot salinity readings are shown (see key).

Salinity was measured as total dissolved salts (TDS) using a portable, temperature-compensated refractometer (American Optical Company, USA) calibrated with standard seawater (Charlottenlund, Denmark) and expressed as parts per thousand (°/₀₀).

2.5 SOIL PROPERTIES

Soils properties were examined at three depths down the soil profile: 0-5 cm, 10-20 cm and 40 cm, thus including changes both above and within the main zone of the cable roots of the mangroves. Samples were collected in air-tight 250 ml soil tins by direct excavation or by coring with a 5 cm diameter graduated perspex corer. Salinity of interstitial soilwater was measured on fresh soil samples by the saturated soil paste technique (Richards 1954). Pastes were prepared from field-moist soils in the laboratory by wetting, where necessary, beyond field capacity and centrifuging the paste (10 minutes; 2000 rpm) to extract interstitial water. TDS was subsequently read and corrected for dilution. Chloride concentration of the soilwater extracts was measured using a chloride ion probe (Model 96-1700, Orion Research Inc, Mass, USA) connected to an ion analyzer (EA 940, Orion Research Inc, Mass, USA) calibrated with solutions of NaCl. Soil moisture was measured by drying pre-weighed field-moist soils to constant weight in a ventilated oven and expressing moisture on the basis of percentage of soil dry weight. Particle size fractions of soils were obtained by the hydrometer method (Bouyoucos 1962) using air-dried soils passed through a 2 mm sieve. Organic matter was estimated by combustion of oven-dried soils (110°C) in a muffle furnace (700°C). Texture was determined according to the international fractions of Marshall (McDonald, Isbell, Speight, Walker and Hopkins 1984). Soil colour was read from soil colour charts (Munsell Color, Md, USA,1975 edition). Soil pH was measured on dried soils passed through a 2 mm sieve treated with 0.01 M $CaCl_2$ and shaken for 1 hour. The pH of the supernatant was read using a Ross combination pH electrode (Model 8155 SC, Orion Research Inc, Mass, USA) connected to an ion analyzer (see above).

3. RESULTS

3.1 EXTENT OF MANGALS

Areas of living mangals within the limits of the 19 maps surveyed are given in Table 1. These are shown for each of the maps whose limits are outlined in Figure 2. The areas have been designated as zones of "*Avicennia* " and "*Rhizophora* " based on the clear colour separation apparent between these two mangroves in false-colour infra-red aerial photographs. Other members of the Rhizophoraceae family occurring in the region, viz *Ceriops tagal* and *Bruguiera exaristata*, have similar leaf colour to *Rhizophora stylosa* and, at the elevation of the survey photographs, it is impossible to differentiate one species from another. The error this introduces into the figures is likely to be small considering the dominance of both *Avicennia marina* and *Rhizophora stylosa* in mangals on this coast. Of the 59 km^2 of living mangals between Cape Preston and Cossack, "*Avicennia* " makes up nearly 87% and "*Rhizophora* " the remainder. The latter are best represented at Point Samson, east of Popes Nose Creek (map 7 in Figure 2; Table 1) and also south-west of Dampier (map 4 in Figure 2; Table 1). Of the 70 km^2 of vegetation surveyed about 12 km^2 is now dead. Over 95% of this area is associated with trees permanently ponded within the salt evaporator.

3.2 SOURCES OF DISTURBANCE TO MANGALS

Mangals in this region are, for the most part, unspoiled, for example those on the islands in the Dampier Archipelago (Figure 2) and those occurring as discrete communities within small embayments around the Burrup Peninsula, such as Watering Cove and Cowrie Cove (Figure 3a). Several disturbances impinge on mangroves in the region (Table 2) and their impact ranges from relatively minor deterioration involving partial defoliation or death of a few trees, to widespread death, exemplified by the permanent ponding of mangroves in the salt evaporator. Other sites now displaying mass mortality of mangroves, for example at Pope's Nose Creek and Cossack, are associated with roads truncating landward sections of the mangals. Disturbances at sites visited for this study are described briefly below. Sites are presented according to location (see Figures 2 & 3).

Table 1: Areas of living mangal (km²), Cape Preston to Cossack, Western Australia. Map numbers refer to areas shown in Figure 2. The total area of each map is 216 km² except maps 1 and 19 which include the limits of the aerial photographs and have mapped areas of 111 and 150 km² respectively. The proportion of each map associated with mangals is shown as a percentage.

Map Number	Total Living Mangal (km^2)	'Avicennia' % map	'Avicennia' area (km^2)	'Rhizophora' % map	'Rhizophora' area (km^2)
1	5.02	4.28	4.75	0.24	0.27
2	4.28	1.93	4.16	0.06	0.12
3	1.94	0.86	1.85	0.04	0.09
4	14.20	4.67	10.10	1.90	4.10
5	3.98	1.84	3.98	0	0
6	8.56	3.91	8.45	0.05	0.11
7	6.75	2.48	5.35	0.65	1.40
8	2.91	1.06	2.29	0.29	0.62
9	2.74	1.20	2.59	0.07	0.15
10	0.70	0.29	0.62	0.04	0.08
11	0.62	0.20	0.43	0.09	0.19
12	0	0	0	0	0
13	0.11	0.03	0.06	0.02	0.05
14	1.73	0.67	1.45	0.13	0.28
15	0	0	0	0	0
16	0	0	0	0	0
17	0.64	0.27	0.59	0.02	0.05
18	0	0	0	0	0
19	5.06	3.13	4.85	0.13	0.21
Total	59.28	26.82	51.54	3.73	7.74

3.2.1 WITHNELL BAY

Mangroves are best developed on the undisturbed north-east shore (Figure 3a). A well-defined tidal creek drains the mangal which is dominated by *Avicennia* and with *Rhizophora* along the creek margins. A narrow, fringing stand of *Avicennia- marina* and *Ceriops tagal* occurs along the back of the salt flat and there are smaller stands of *Ceriops* mixed with *Bruguiera exaristata* along the rocky shores of the bay. A liquid natural gas (LNG) plant has been constructed on the south-west shore as part of the NorthWest Shelf Gas Project (NWSGP). The impact of this development on the system was not examined for this paper.

3.2.2 KING BAY CAUSEWAY

A causeway constructed in 1981 truncates the landward limit of *Avicennia* at King Bay and carries the road from Dampier/Karratha to the NWSGP sites at King Bay and Withnell Bay (Figures 3b & 4b). Tidal exchange with the large salt flat landward of the road is made possible through a large cement culvert built under the road (Figure 4b) which apparently offers little resistance to flushing, allowing seawater to wet to the back of the salt flat on high spring tides. The mangal is dominated by *Avicennia* and *Rhizophora*, the latter well-developed along the creek margins. Impact of the road on the mangal has been relatively minor. The seaward side of the causeway consists of *Avicennia* (2-3 m) and smaller stands of *Rhizophora* (3-4 m) of which a small section, next to the road, has been cleared and filled with rock rubble during road construction; the mangal to landward is entirely *Avicennia*

(1-2 m). Seedlings of *Avicennia* are growing successfully on each side of the causeway. The salt flat has been disturbed from construction of a trench for a gas pipe across the salt flat parallel to and just landward of, the road. The trench has since been filled in.

Table 2 Sources of disturbance to mangals in the Dampier-Cossack region, Western Australia. Locations with examples of disturbance are those shown in Figure 2.

Source of Disturbance	Effect	Location	Impact/Extent
Road construction	altered drainage rates diminished tidal recharge increased salinity chronic flooding altered soil structure erosion.	G, J	mass mortality
Dust from unsealed roads/ ore stockpile	heavy dust coasting on leaves of mangroves	D,F,J, K	unknown but widespread; possible effect on stomata
Site construction			
dredge spoil	asphyxiation of roots	B, H	localized mortality
salt evaporator ponds	permanent ponding hypersalinity	see Figure 2	mass mortality
salt bitterns ponds	increased salinity (?) altered tidal gradient (?)	E	localized mortality
harbour	interference with tidal exchange removal of mangal	H	unknown localized mortality
jetty	removal of mangal	B	localized mortality
Effluent			
release of freshwater used as dust suppressant at ore stockpile plant	not examined	F	unknown; possible input of ore dust to sediments
nutrient release from sewage pond	not examined	J	unknown; enhanced growth of mangroves apparent
Recreation			
off-road vehicles	erosion of salt flats ponding of tidal water scouring/removal of blue-green algal mats	D, E	mortality of mats

3.2.3 SOUTH-WEST KING BAY

This is an undisturbed and sheltered mangal with well-developed zonation from tall, closed *Rhizophora* woodland seaward, to monospecific closed *Avicennia* scrub landward, backed by a well-developed salt flat and a narrow and sparse low scrub of *Avicennia* fringing the back of the salt flat next to the rocky hinterland (Figures 3b & 4a). Small stands of *Ceriops* and *Bruguiera* fringe the rocky shores of the tidal creek in the seaward zone. This mangal has been the site of previous studies of blue-green mats, which cover about 0.5 ha of the salt flat (Paling 1983). The mangrove zonation has been described in detail (Semeniuk 1983). It was used in the present study for measurements of salinity in relation to tidal exchange, and for physiological studies on *Avicennia* (Gordon, in preparation). Along the rocky eastern shore of the seaward zone of this mangal a 15 m wide section of fringing *Rhizophora* was removed during construction of a small jetty. The jetty has since been removed and with it some of the construction spoil. *Rhizophora* seedlings are now re-establishing at the edges of the cut section. Access is by unsealed road.

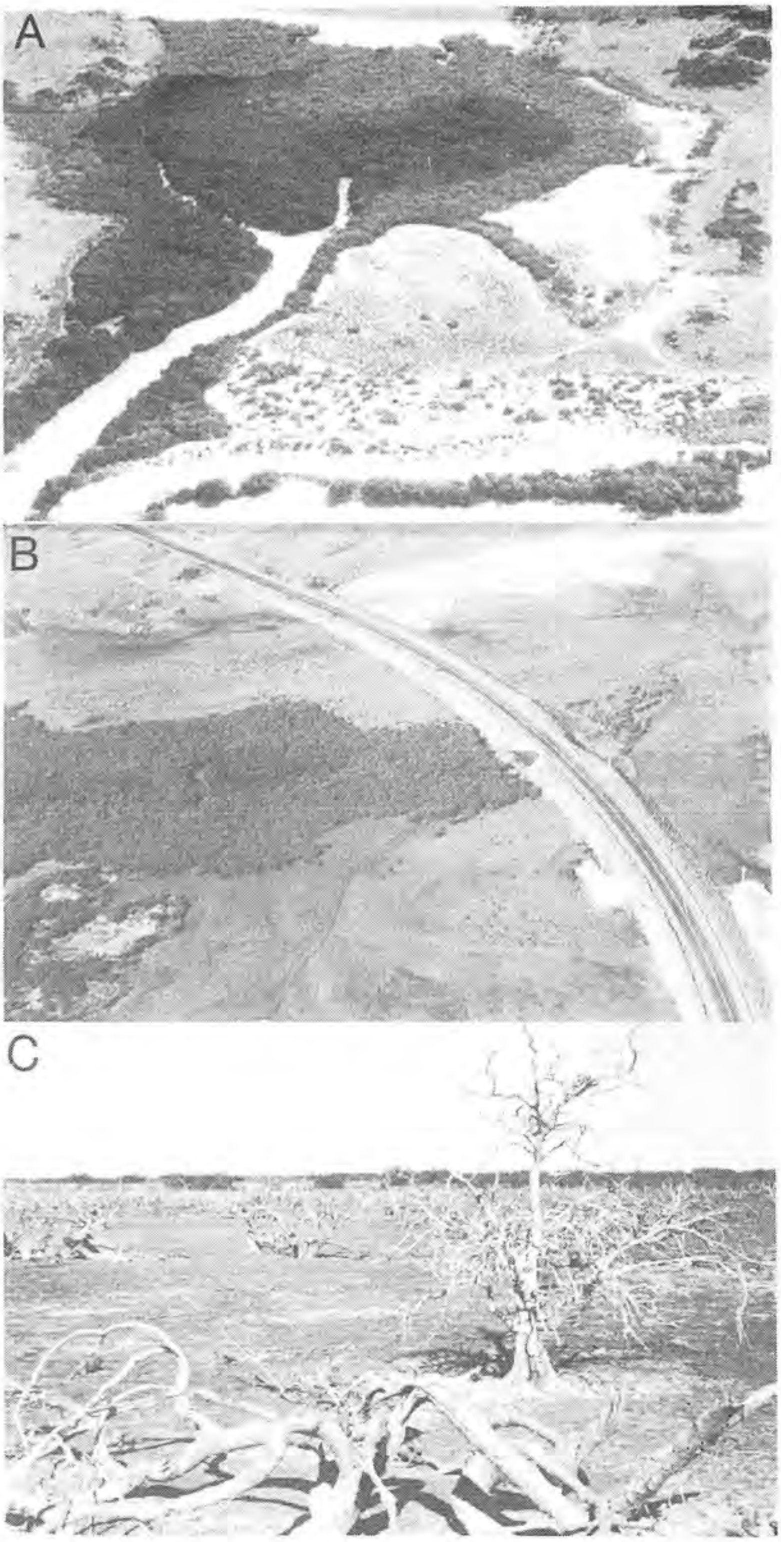


Figure 4. General views of the study area A: aerial view of the undisturbed and sheltered mangal at south-west King Bay showing the distinct zonation between the seaward *Rhizophora* zone, landward *Avicennia* zone and the salt-flat behind B: road truncating the landward zone of the mangal at King Bay. A large cement culvert constructed under the road allows exchange of seawater sufficient to wet to the back of the salt flat on high spring tides C: dead *Ceriops* and *Avicennia* in the tidally-restricted mangal landward of the Cossack causeway. Tidal exchange at this site has been altered through construction of the road perpendicular to the main tidal creeks draining the mangal. The site now suffers ponding of seawater on equinoctial high spring tides landward of the road.

3.2.4 KING BAY "SPOIL AREA 4"

This is the most disturbed mangal in King Bay and is within the boundaries of a supply base constructed by Woodside Offshore Petroleum Pty Ltd as part of the NWSGP (Figure 3b). Dredge spoil from construction of the harbour in the supply base was stockpiled behind a bundwall constructed in April 1981. Fine sediments from the stockpile washed through the porous wall and buried a large section of the mangal (May 1981). Up to 2 m of spoil was deposited on the mangroves, mostly *Rhizophora*, adjacent to the bund wall. The natural elevation of the tidal gradient was also altered by the deposition of spoil and presumably contributed to the demise of the trees through reduced wetting. The mangal deteriorated rapidly and was subsequently cut down and removed over a 3 month period in 1982. Further dying-off was apparent in subsequent sequential low-elevation aerial photographs taken over the next few months (supplied courtesy of Woodside Offshore Petroleum Pty Ltd). Based on these photographs the area of mangal removed by death and clearing seaward of the bund wall is calculated to be about 1.4 ha. Some revegetation by seedlings of *Rhizophora* and *Avicennia* was apparent at the existing landward fringe at the time of the survey. The remaining seaward stands of *Rhizophora* are apparently healthy. Access to the site is restricted.

3.2.5 LEVEE 24, DAMPIER SALT PTY. LTD.

Situated in south-west Nickol Bay (Figure 3c) the mangal consists of monospecific *Avicennia*. Behind the main vegetation zone is a well-developed salt flat supporting extensive blue-green algal mats and shrubby halophytes (Paling 1983). A salt bitterns pond constructed across the back of the salt flat separates this from the rest of the mangal. The pond was used originally (1969-1974) to contain the residual 'brine' solution (bitterns) following extraction of salt from the evaporation ponds of the salt evaporator further west, but is now disused and bitterns are discharged directly into Nickol Bay (Figure 3c). Mangroves fringing the landward margins and headwaters of a tidal creek at the south-west corner of the salt flat close to the wall of the bitterns pond are now showing signs of stress (depauperate leaf canopy) and some are dead. Ponding of seawater occurs next to the wall following ebb tide, though there is no physical restriction to tidal exchange up to the wall. Entrance to the bitterns pond is restricted.

3.2.6 NICKOL BAY, KARRATHA TOWNSITE

This is part of a continuous but narrow belt (250 m) of *Avicennia* fringing 10 km of the Nickol Bay foreshore (Figure 3c). Salt flats are not well-developed near the townsite but are extensive further west. The mangal is healthy with numerous seedlings establishing. Mature trees are gnarled and recumbent and presumably very old. They form a well-spaced, but closed woodland. The site is disturbed at present by widespread damage to salt flats and associated blue-green mats by off-road vehicles. Tyre tracks scour the edges of the mats, cut into the salt flats and pond tidal water (Paling 1983). The mangal close to the townsite is in a location popular for recreation where vehicles are driven on the beach. Located on tidal flats with a shallow topographical gradient, the mangal provides a buffer zone between the townsite and the sea.

3.2.7 SAM'S CREEK

A tidal creek drains a small mangal of about 30 ha, located behind a series of beach dune ridges (Figure 3d). The vegetation is dominated by *Avicennia* and small stands of *Rhizophora* occur along the creek margins. The creek mouth is used as a fishing boat harbour. There is no restriction to tidal exchange. The salt flat communicates with that of the Pope's Nose Creek system further south (Figure 3d). These drain to the north and south-east, respectively. The mangal is superficially healthy. Freshwater used for dust-suppression as part of the operation of the Robe River Iron Associates iron-ore exporting plant at Cape Lambert is diverted into the back of the creek. This freshwater source may have stimulated growth of mangroves locally as there are stands of healthy tall, closed *Avicennia* along the drainage channel. The freshwater supply now entering the creek is likely to be reduced in the future when the company begins to recycle its water. There has been some localized mortality of trees here which occurred suddenly for unknown reasons (S. Vellacott, pers. comm.) Dust from operation of an iron-ore pellet plant was previously a problem at the site but this operation has been disbanded since 1979. Heavy dust loads on the leaves may have stressed some mangroves here presumably by affecting the functioning of stomata.

3.2.8 POPE'S NOSE CREEK

This creek drains a healthy and extensive mangal whose seaward zone contains the most luxuriant stands of *Rhizophora* along this section of the coast (Figure 2; Table 1). The creek and mangal is truncated by the Roebourne-Point Samson Road and where this crosses the creek it restricts tidal exchange (Figure 3d). Landward of the rock-fill bridge about 6 ha of mangroves in the southern section are now dead. These consist of a well-spaced, mixed scrub of stunted *Ceriops tagal* and gnarled *Avicennia marina* shrubs. This mortality has effectively extended the salt flat about 200 m. The bridge across the creek was originally a trestle one (1965) but was converted to a rock-fill causeway in 1966 using stone quarried from the Aboriginal Land's Trust Reserve (Reserve No 30433) located south of the bridge. Further road construction immediately north-east of the bridge has been recently completed. Like the superseded sealed road and the now-disused tramway (1920's) which preceded that, the new road causeway cuts off small sections of healthy mangroves. These isolated sections are recharged with seawater through small culverts under the road. Localized erosion is now apparent around roots of trees at the mouth of the western most culvert, presumably through the action of concentrated water-flow during flood tides. Siltation from the deposition of causeway sand has resulted in death of some trees (C Nicholson, pers comm).

3.2.9 JOHN'S CREEK

The site is part of the large, healthy mangal seaward and north-east of the Pope's Nose bridge (Figure 3d) and has an extensive seaward *Rhizophora* zone backed, to landward by *Avicennia*. It has been disturbed by dredging and dredge spoil during construction of a fishing boat harbour at the mouth of the creek. The spoil has smothered and killed some of the fringing *Avicennia*. Jetty construction has widened the natural break in the fringing stands of *Rhizophora* on the north shore. Originally a 6 m stone wall was planned to cross the harbour near the creek mouth. This was not recommended as providing suitable flushing (unpublished records; Department of Conservation and Environment, Western Australia) and was, instead, constructed at 3.5 m by the contractors. Although this does not impede seawater exchange during recharge some scouring has lead to undermining of roots and the collapse of some trees (C. Nicholson, pers. comm.).

3.2.10 COSSACK CAUSEWAY

This mangal has almost identical problems to that at Pope's Nose Creek. About 7 ha of a *Ceriops-Avicennia* community has been killed landward of a causeway connecting the town of Cossack with the Roebourne-Point Samson Road. This causeway truncates the landward section of a large and healthy mangal which extends along the western shoreline of Butcher Inlet (Figures 3e & 4c). Seaward of the road the mangal is a healthy open scrub of stunted, *Ceriops tagal* and *Avicennia marina* (1-2 m). Only a few of the original *Avicennia* have survived landward of the road, for example those fringing the tidal creeks and small stands remaining on the tidal flats close to the road None of the *Ceriops* trees making up the original community has survived landward of the road. There has been widespread colonization by *Avicennia*, however, along the gravel verges of the road. Behind the now-dead landward limit of vegetation is an extensive salt flat supporting blue green algal mats. This salt flat ajoins another draining a mangal further north. The now-disused tramway to Cossack was constructed at the highest elevation of the tidal gradient, along the dividing line between both salt flats (Figure 3e). This has been breached in places so that water can communicate between the two salt flats on high spring tides.

The major sources of seawater for tidal recharge in the mangal are two creeks feeding the Harding River, near the mouth of Butcher Inlet (Figure 3e). These are truncated by rock-fill under the road and would otherwise fill and overflow at the same time into the mangroves now separated by the road. Water exchange under the road is reduced to slow seepage rather than sheet flow where the road crosses the creeks perpendicular to the direction of water flow. The result, like the Pope's Nose Creek system, is to introduce a depth differential each side of the road during inundation (see below). Secondary flow is also permitted through three small culverts (69 to 96 cm long and 46 to 61 cm high; information courtesy of the

Shire of Roebourne). These culverts act as fast-flowing drains under spring flood tides, water flowing rapidly through openings under the road and along discrete drainage channels formed through resulting erosion of the mangrove soils. The mangal is readily accessible from the road and has been used for gauging the effect of this sort of disturbance on tidal exchange and soil properties (this paper) and water use and salt exchange by the trees (Gordon, in preparation).

3.2.11 COSSACK TOWNSITE

This site is included to draw attention to a narrow (5-10 m wide), healthy mangal fringing the western shoreline of Butcher Inlet (Figure 3e). Species diversity is high in this stand, with six of the seven species which occur at this latitude growing together. The township was originally a port named Tien Tsin (it was renamed Cossack in 1871) and was the centre of a thriving pearling industry before the gradual silting up of the river mouth reduced its value as a harbour. Historical photographic records in the Cossack museum suggest that these fringing mangroves are regrowth, as mangroves were probably removed at the end of last century during construction of the wharf and for small timber and firewood. Impact of a rapidly-increasing population on the mangroves during the peak development and operation of the port last century is unknown. Disturbance to the mangroves today is small, though dust from road-traffic using the unsealed road is heavily deposited on leaves of the trees both here and along verges of the entire Cossack road causeway. The impact of dust deposits on the mangroves has never been assessed despite being a common problem throughout the region wherever unsealed roads and ore stockpiles occur close to these communities.

3.2.12 WICKHAM SEWAGE POND

A pond for the Wickham townsite was constructed adjacent to the salt flat north of the breached Cossack tramway (Figure 3e). Outflow from a channel in the south-east corner of the pond contributes nutrients to a nearby mangal. There is prolific growth of *Avicennia* and *Rhizophora* in the channel near the pond (Paling 1983) with permanent surface water near the outfall. Nutrients entering the salt flat via this source could be carried east to the mangal at the Cossack causeway during equinoctial high spring tides when tidal penetration is maximum..

3.3 TIDAL EXCHANGE

3.3.1 FREQUENCY AND MAGNITUDE OF TIDAL RECHARGE

Mangroves are generally restricted to a zone bounded by mean sea level and mean high water spring tides. The natural topography of the tidal flats, with their shallow gradient set by existing landforms, governs the energy dissipation of the tides, the frequency of inundation of the trees and the water depths experieced by the trees during inundation. The Dampier-Cossack region lies within the north-west Australian tidal zone of which a distinguishing feature is a large spring tidal range (Easton 1970), typically 4 to 5 m at this latitude. Maximum tides are nearly 6m (Anonymous 1984; 1985). Tidal fluctuation is governed by the interaction of the lunar and solar cycle and is regulated by several interacting harmonics, dominated by two components with periods of 12.4 and 12 hours, respectively (Easton 1970). These produce semi-diurnal tides. Spring tides occur approximately each fortnight when these two harmonics coincide. Maximum tidal amplitudes occur during the equinoxes and are smallest around the time of the winter solstice. Consequently the capacity to recharge the landward zone of the mangal diminishes during June and July, and is greatest around March and September. Thus, for the landward locations at King Bay and Cossack, only about 56% and 45%, respectively, of annual flood tides wet the sites (annual averages of monthly figures; Figure 5). The reduced frequency of wetting around the winter solstice is exacerbated by restricted tidal-exchange such as that produced by the causeway at Cossack (Figure 5). Soils dry out for longer intervals than normal (Figure 6) and this influences the salinity regime. A general relationship between tidal recharge and soil salinity is shown in Figure7 using data from different locations. At landward, infrequently-wetted sites soils are hypersaline while those fringing the seashore retain salt concentrations closer to ocean salinity.

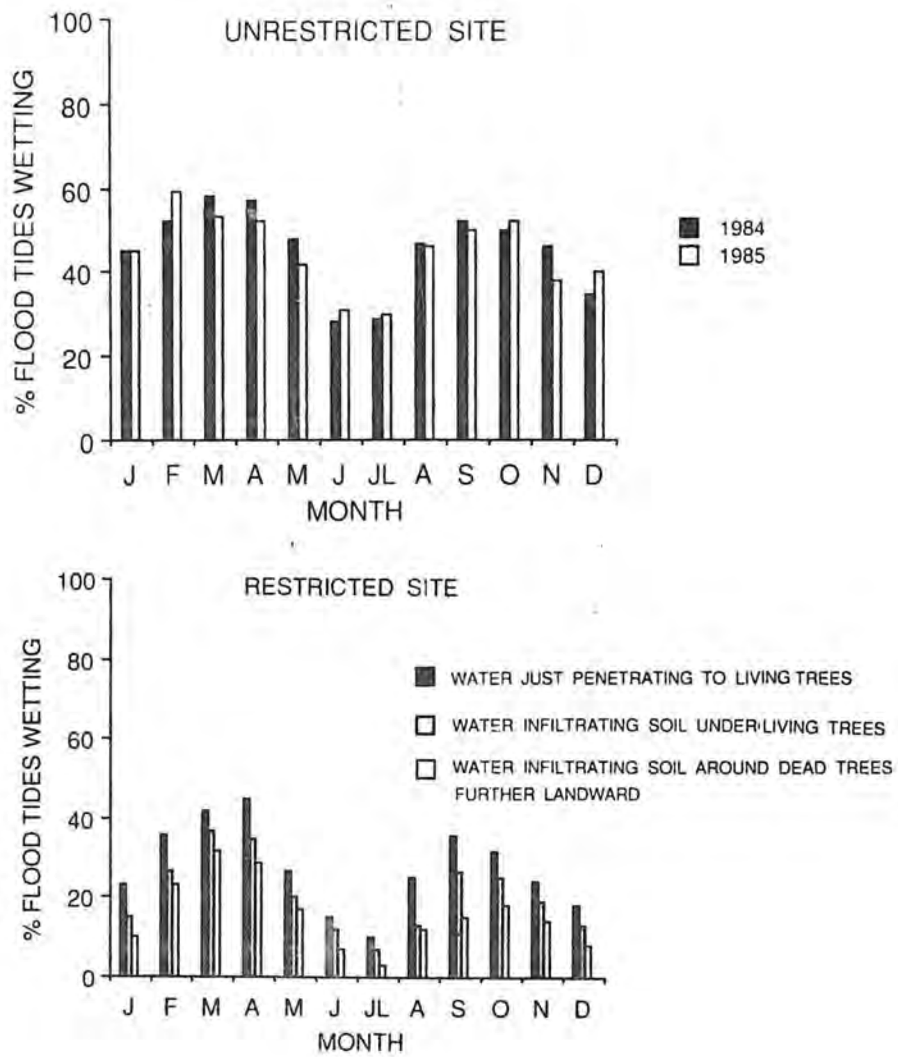


Figure 5. Differences in the frequency of flood tides wetting the landward tidally-restricted and unrestricted mangal each side of the Cossack causeway. Figures shown are percentages of the total flood tides for each month. Figures shown in lower histogram are for 1985 only.

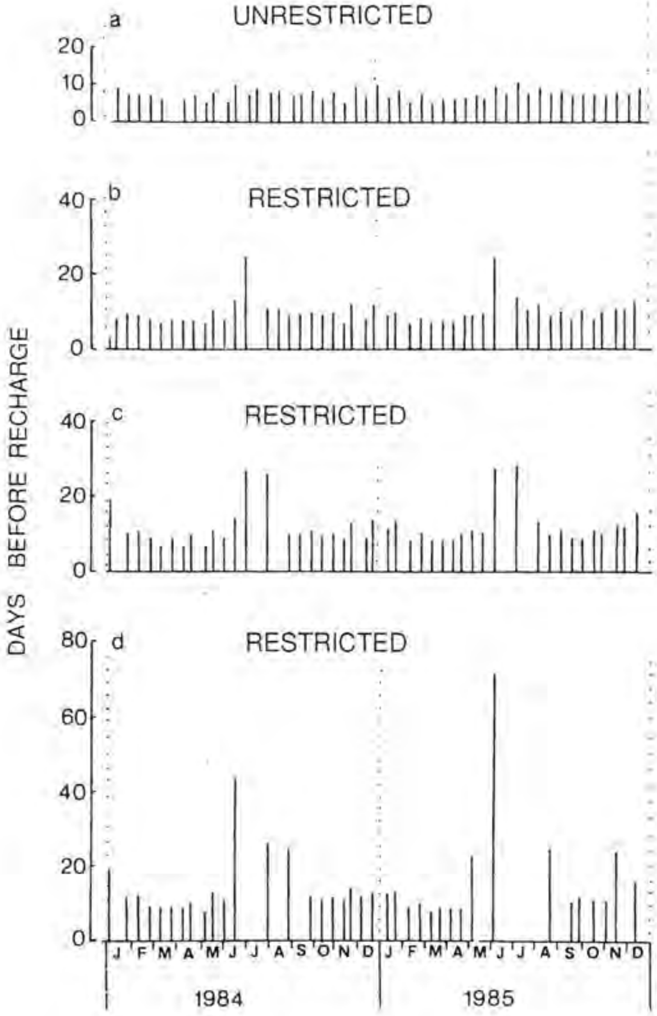


Figure 6. Seasonal changes in the duration of drying between periods of tidal recharge on each side of the road at Cossack, calculated from predicted tides for 1984 and 1985 (see text). a: the tidally-unrestricted mangal b: the tidally-restricted mangal with flood tides of sufficient magnitude to just wet to the remaining living trees c: tidally-restricted mangal with seawater wetting to the remaining living trees for sufficient time to infiltrate surface soils d: tidally-restricted mangal with seawater wetting and infiltrating soils further landward, within the zone of dead trees.

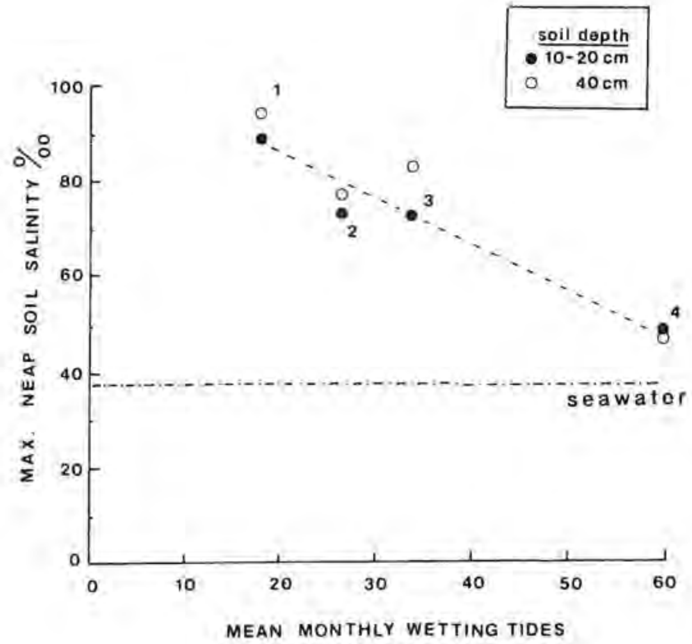


Figure 7. Soil salinity as a function of frequency of tidal wetting under living mangroves. Data shown are maximum neap salinities at two soil depths in different locations 1: tidally-restricted mangal landward of the Cossack causeway 2: tidally-unrestricted mangal seaward of the Cossack causeway 3: tidally- unrestricted mangal at south-west King Bay 4: tidally-unrestricted mangal fringing the seashore at the Cossack townsite. The dashed line depicts seawater salinity.

3.4 SALINITY

3.4.1 SPATIAL VARIATION

Groundwater salinities measured across sections of different mangals in the region are shown in Figure 8. Spot salinity readings were also made on groundwater at a number of the sites where there is disturbance and death of trees (see Figure 3 for locations and Table 3 below for salinity values). The salinity range measured across the main vegetation zone of mangals was typically from seawater salinity at the seaward fringe, increasing up to 85 ‰ to landward where the main vegetation zone contacts the salt flat. This is consistent with previous readings from the region (see Semeniuk 1983; 1985). *Rhizophora* was best developed towards the front of the mangals where tidal exchange is sufficiently frequent to maintain salinities below 50 ‰. Very high salinities occur across salt flats. Pits dug at the boundaries between the unvegetated salt flat and the landward limit of the main vegetation zone of the mangroves showed that salt content of groundwater was lowered sharply wherever there were mangroves (for example King Bay in Figure 8). Salinities in the tidally-restricted dead *Avicennia -Ceriops* community at Pope's Nose Creek were mostly well above the reported tolerance limit for mangroves, grading from 150 ‰ under dead trees at the extreme landward limit of the original living vegetation down to about 80 ‰ closer to the creek at the existing boundary between living and dead trees (Figure 8). Dead trees found in the disturbed locations sampled were all associated with salinities above 90 ‰ (Table 3). In some cases salinities were extremely high, for example 155, 137, and 156 ‰ in soils under one stand of dead trees on three different days at the Levee 24 site. This site also displayed the highest salt concentrations of any of the salt flats visited, with salinities above 200 ‰ next to the wall of the bitterns pond (Figure 8).

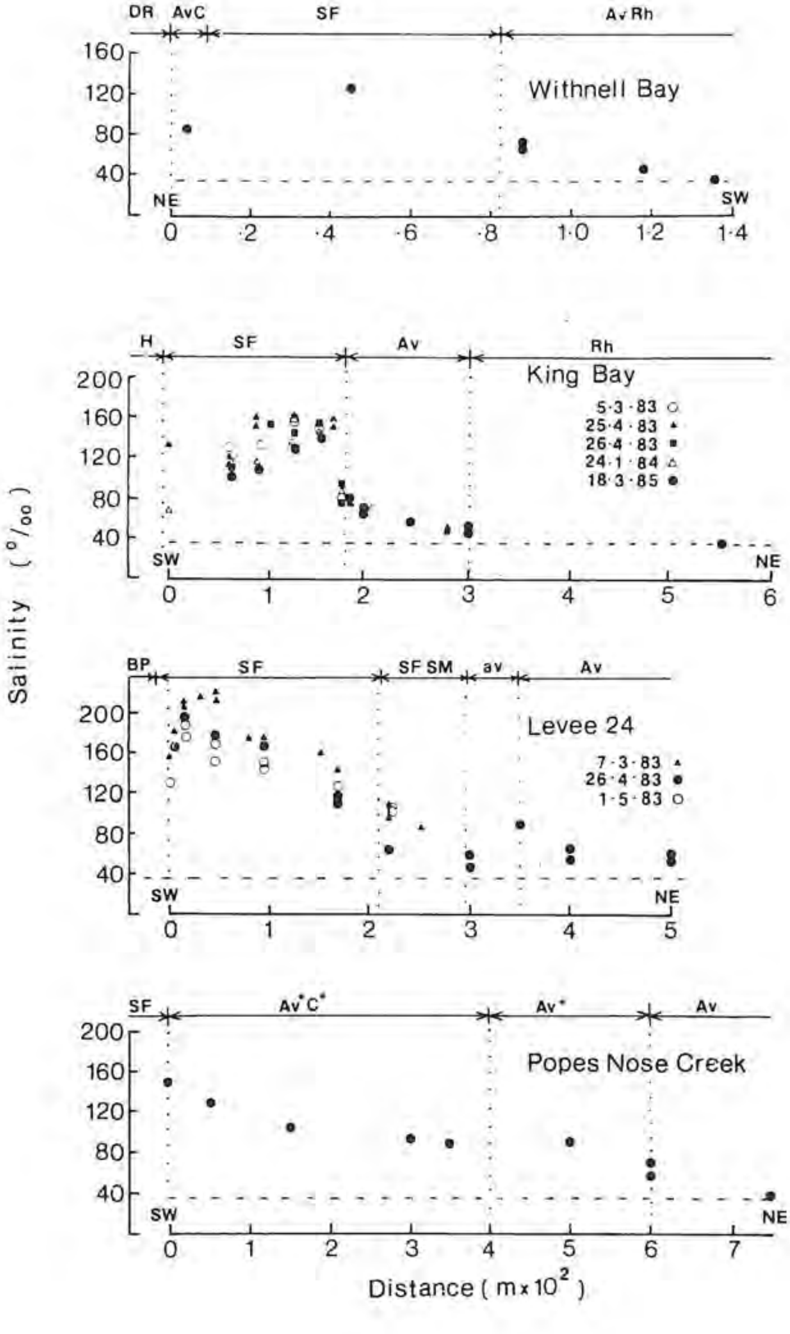


Figure 8. Groundwater salinity across sections of selected mangals in the study area. See Figure 3 for locations of transects. Dates when sampling was repeated are shown. DR: dune ridge; H: hinterland; SF: salt flat: BP: wall of bitterns pond; Av: Avicennia; av: Avicennia seedlings; C: Ceriops; Rh: Rhizophora; SM: samphires; Av*: dead Avicennia; C*: dead Ceriops SW: south-west; NE: north-east. Data for March from King Bay and Levee 24 are from Paling (1983).

Table 3. Groundwater salinity measurements at disturbed sites in the Dampier-Cossack region. Refer to Figures 2 and 3 for sampling locations described below. Figures shown are either single readings or a range, measured at low tide in April 1983. Sites which were inundated by the flood tide preceding the measurement are shown with an asterix.

Location	Salinity (°/oo)	Comment
King Bay causeway		
Extreme landward limit of mangal*	70	*Avicennia marina*. Tree height 2-3 m. Pneumatophores present. Seedlings establishing.
Landward side next to roadside*	52	*Avicennia marina*. Tree height 3-4m. Pneumatophores present. Seedlings establishing.
Seaward side next to roadside*	50	Some mangal cleared next to roadside. *Avicennia marina*, 4-5 m. Some *Rhizophora stylosa*, 4-5 m. *Avicennia* seedlings establishing.
150 m seaward of causeway at the edge of the mangal*	70	*Avicennia marina*, 1-2 m. Numerous *Avicennia* seedlings growing. Many *Rhizophora* seedlings washed in here but few are successfully establishing.
Levee 24, Dampier Salt		
Next to bitterns pond wall*	137-156	Under dead *Avicennia*. Trees are 1-2 m tall, 3-4 m across, gnarled and recumbent. Bole diameters 5-10 cm. No pneumatophores. Ponding of water on ebb tide.
Next to bitterns pond wall*	70-90	Under moribund *Avicennia marina* with some healthy leaves. Tree 'growing' amongst zone of dead mangroves. No pneumatophores.
150m seaward of bitterns pond wall*	112-120	Under dead *Avicennia marina*
Popes Nose Creek		
Each side of rock-fill bridge*	37	Healthy *Rhizophora stylosa*, *Avicennia marina*.
Landward side of old road in truncated mangal*	40-50	
Landward side of new road in truncated mangal*	65-70	*Avicennia marina*, trees healthy, seedlings growing, pneumatophores present.
Seaward side of road, in mangal*	56-58	Healthy *Avicennia marina*. Seedlings growing.
Cossack causeway		
Landward side next to roadside	92-94	In zone of dead *Avicennia*.
20 m landward of causeway	102-104	In zone of dead *Avicennia*.
150 m landward of causeway	117	In zone of dead and moribund *Avicennia*.
10 m landward of road at southern entrance to causeway	146	In zone of dead and moribund *Avicennia*.
10 m seaward of road at southern entrance to causeway	122-132	Under small stand of dead *Avicennia*.
100 m seaward of causeway*	77	In zone of healthy *Avicennia*, 2-3m.

3.4.2 TEMPORAL VARIATION

Changes in groundwater salinity measured on different dates from the same locations at low tide give an indication of temporal variability in the salt content of the landward hypersaline sections of the mangals (Figure 8). The influence of surface tidal recharge on groundwater was examined in more detail in the landward mangal at south-west King Bay by taking readings between successive flood tides over part of a tide cycle, thus including a period when the sites were wetted and a period without tidal recharge (Figure 9). These readings were made from permanently-seated sampling pipes tapping the groundwater under the salt flat and in the landward *Avicennia* woodland. Groundwater salinities are not markedly affected by incoming surface seawater, at least at the scale of the sampling frequency used here (about 12 hours in Figure 9a). Measurements made about 15 months apart similarly indicate constancy in groundwater values here. Some of the sites displayed noticeable fluctuations in salinity over the tide cycle, particularly sites 2,3 and 4. These are all located close to the tidal creek and this may be a reason for their similar behaviour. The January readings were made following a period of rainfall and lower salinity, presumably from seepage of freshwater, was apparent in the most landward sampling pipe (site 7 in Figure 9a). Free water disappeared from this site after two days. Dilution of normally hypersaline groundwater along the hinterland margins of tidal flats is quite characteristic of groundwater behaviour in mangals of this region under the influence of freshwater input (Semeniuk 1983)

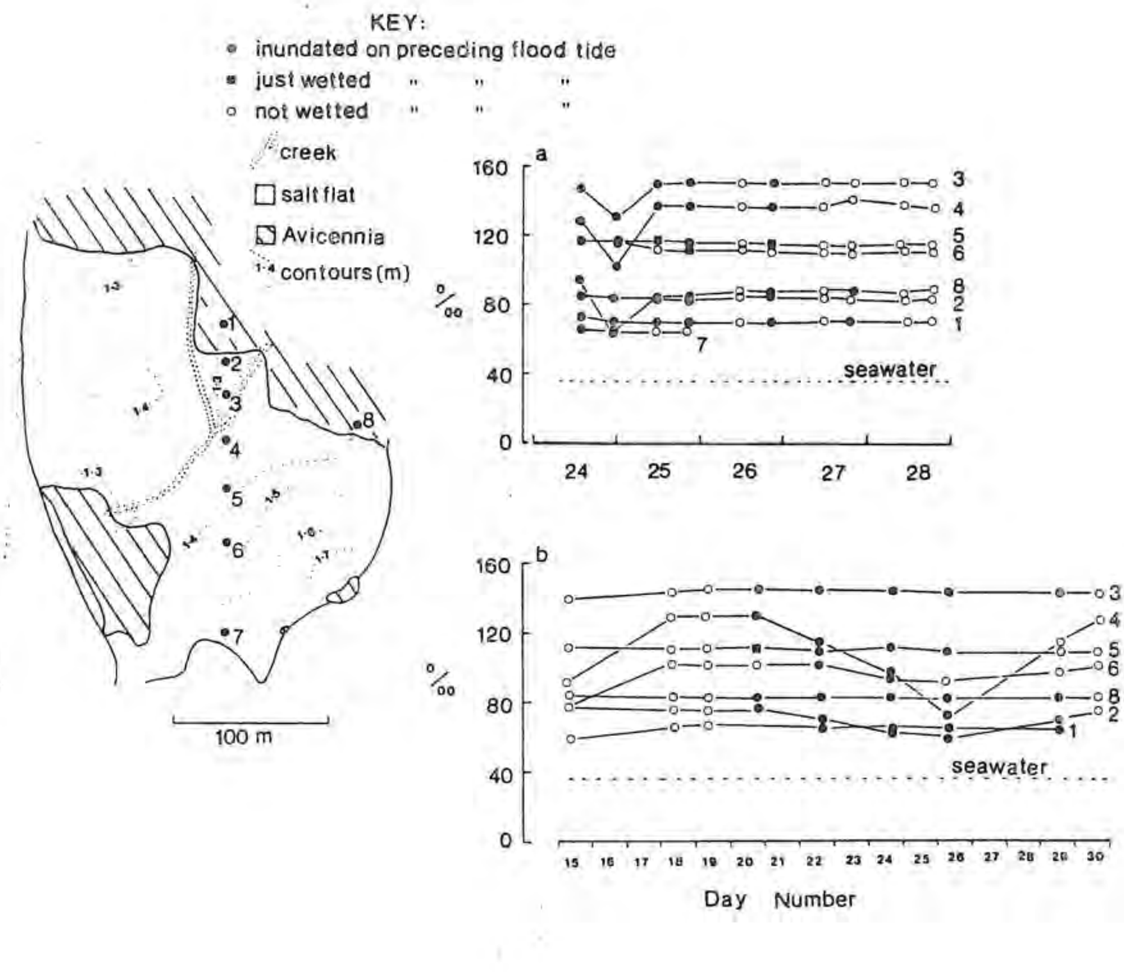


Figure 9. Variation in groundwater salinity across the salt flat and into the landward mangal at south-west King Bay (see Figure 3b) over a changing tide cycle in a: January 1984 and b: March 1985. Readings were taken from permanently-seated sampling pipes between times of recharge. Data for January are measurements following successive flood tides; those in March are not. Day numbers refer to calender days. Those measurements which were preceded by inundation on the previous flood tide are flagged (see Key). The dashed line depicts seawater salinity. Topographical contours (m) are based on arbitrary datum (WA Department of Lands Administration).

The measurements shown in Figure 9 suggest little communication between surface seawater recharging the mangal and the underlying groundwater. These data, however, do not consider the possibility of short-term dilution of groundwater salinity here during inundation. Groundwater salinity was monitored at different soil depths at low tide over a tide cycle in the landward *Avicennia* woodland in south-west King Bay to examine the extent of the diluting effect of inundating seawater (Figure 10). Seawater recharging the site was close to ocean salinity (36 $^0/_{oo}$) and had direct access to subsurface soils through the porous and much-bioturbated sandy loams (see Table 4 below). There was marked fluctuation in groundwater salinity close to the surface in response to inundation. Salt concentrations of water samples collected at this depth were reduced to seawater values during recharge then rapidly returned to hypersaline concentrations before the arrival of the next wetting. Hypersalinity at this depth was re-established at times when the influence of solar evaporation was minimum and suggests that evaporative processes were not a major contributor to this increase but that these changes were more likely the result of physical re-equilibration with higher salt concentrations at depth. Salinity of the water table remains stable at depth throughout the tide cycle irrespective of diminishing duration and frequency of recharge as the tide cycle moves into the neap phase. In the absence of recharge, free-water disappears from the shallow 'rooting zone' as the water table drops. Similar changes in groundwater salinity are apparent under the remaining living trees at the tidally-disturbed site at Cossack before and immediately after tidal wetting (Figure 10D). Seawater arriving at this site was above 40 $^0/_{oo}$ and did not dilute groundwater to the extent measured at King Bay; hypersalinity was again rapidly re-established following wetting.

3.4.3 EFFECT OF VARIABLE TIDAL RECHARGE ON SOIL PROPERTIES AND THE WATER TABLE

Soil properties were sampled at each of the sites used for tidal exchange measurements described above. Those at King Bay and those under mangroves fringing the shoreline at the Cossack township are both classified as sandy-loams, with a high sand fraction (> 70%), relatively low clay content (< 20%) and this is uniform to the maximum depth sampled (0.4 m; Table 4). The sites each side of the causeway at Cossack are relatively finer soils with a higher clay fraction (> 30%). There was a difference in the size-distribution of soil particles each side of the road; the tidally-restricted soils displaying a slightly higher clay fraction and a noticeably lower silt fraction at all depths sampled. Organic matter was greatest in the clay soils at the Cossack causeway and least in the sandy soils at King Bay. Values were slightly higher in the top layer of the profile at each site. At King Bay, the colour classification suggests a soil with distinct horizons, while colour was uniform at the other sites. All soils were slightly basic.

The influence of the change from a drying to a wetting phase of the tide cycle on a number of the soil properties and on the depth of the water table was examined in the landward, tidally-unrestricted *Avicennia* woodland at south-west King Bay (site 1 in Figure 9) to assess the extent to which variable tidal exchange influences the soils and the water supply around the roots of the trees. Depth to free water, groundwater salinity, interstitial soilwater salinity, interstitial soilwater chloride and soil moisture were each sampled on different days over a tide cycle (Figure 11). The predicted tidal amplitudes associated with each phase of the tide cycle are shown. Chloride concentrations of soilwater were also monitored to provide comparative values with chloride concentrations collected from leaf sap and stem sap of mangroves at this site (Gordon, in preparation). All the values shown here (and in Figures 15 & 16 below) were collected at low tide and thus do not include periods where groundwater was diluted by seawater for short intervals during inundation (Figure 9). Consequently some of the variation apparent in the measurements during the wetting phase of the tide cycle will reflect differences in the times samples were collected relative to the previous inundation. The ranges of duplicate samples are plotted and are typically widest for surface (0-5 cm) samples, these being the most heterogeneous. Standard errors of the means, as a measure of the analytical variation, of three subsamples from each sample, were typically < 2% and up to 10% for soil moisture, 0 to 4% for salinity, and typically < 5%, but up to 13%, for chloride.

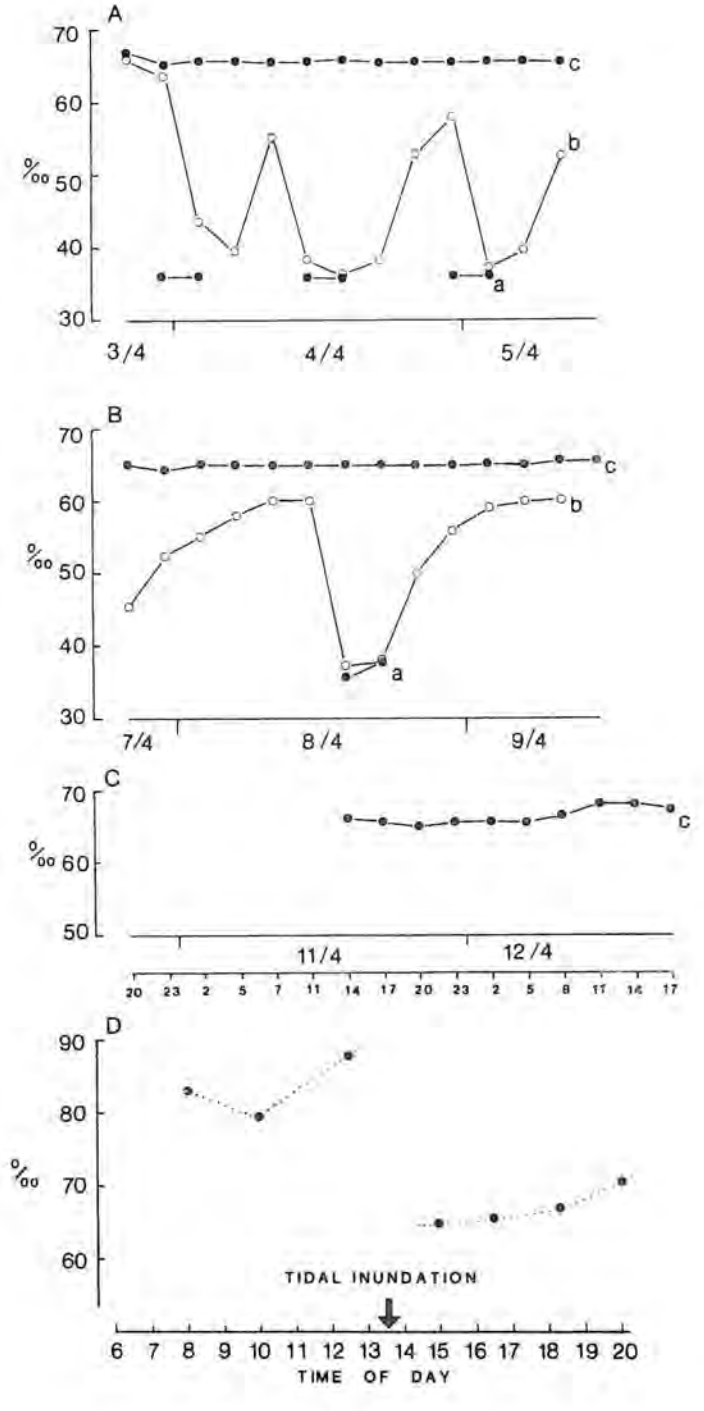
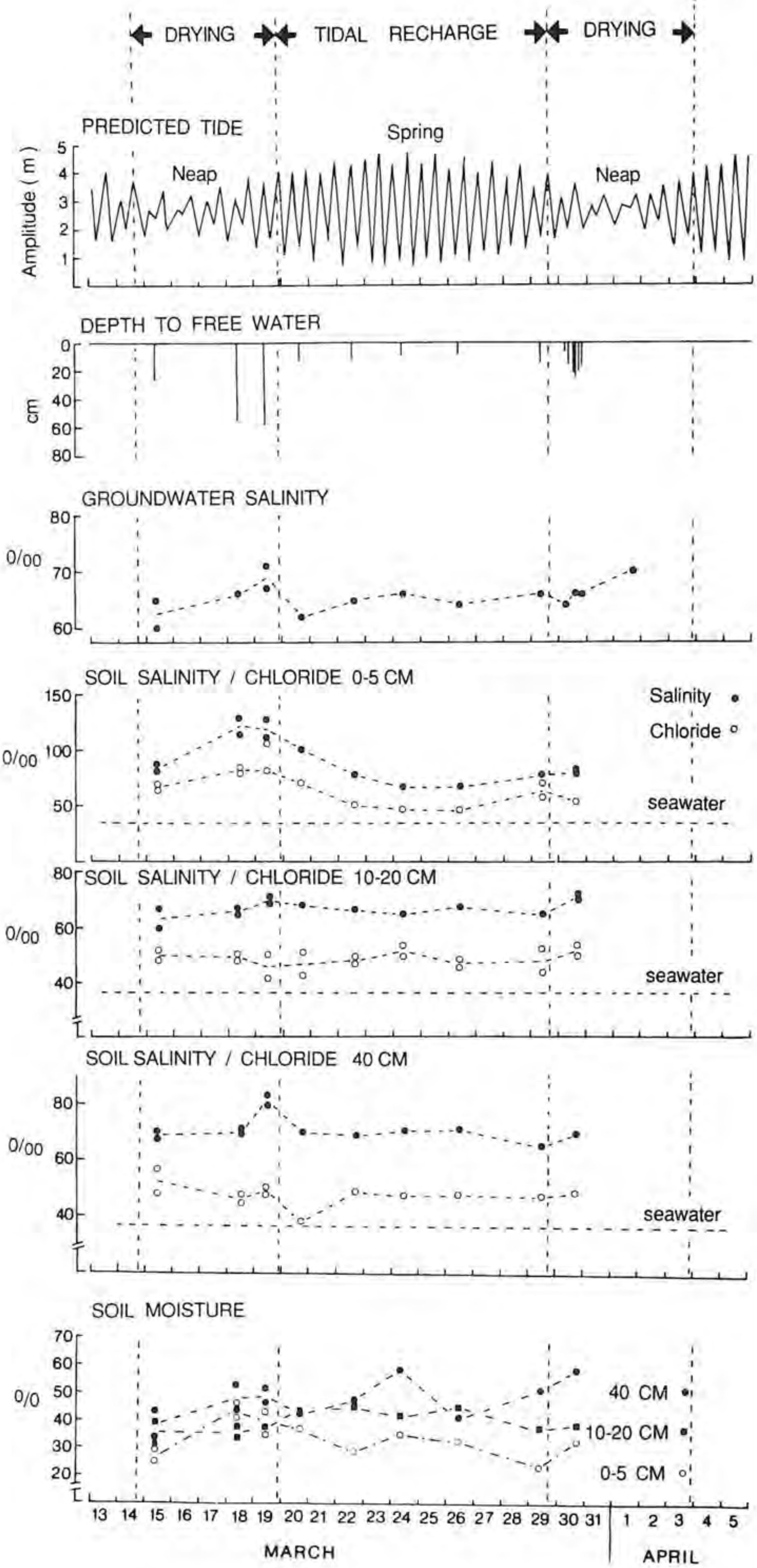


Figure 10. Intratidal variation in groundwater salinity under mangroves. Data shown in A-C are from King Bay (site 1 in Figure 9)) taken at three-hourly intervals over a changing tide cycle (spring to neap) in April 1984. a: surface inundating seawater b: groundwater 10-20 cm below surface c: groundwater 70 cm below surface. Figure D shows short-term changes in groundwater salinity in the tidally-restricted mangal at the Cossack causeway before and after tidal recharge, March 1985. Salinity of inundating seawater in D was 40 $^{0}/oo$. Values shown in D are the last tidal wetting following six days with regular tidal recharge.



DRYING
TIDAL RECHARGE
DRYING
PREDICTED TIDE
Spring
Neap
Neap
Amplitude (m)
DEPTH TO FREE WATER
cm
GROUNDWATER SALINITY
0/00
SOIL SALINITY / CHLORIDE 0-5 CM
Salinity
Chloride
seawater
SOIL SALINITY / CHLORIDE 10-20 CM
seawater
SOIL SALINITY / CHLORIDE 40 CM
seawater
SOIL MOISTURE
0/0
40 CM
10-20 CM
0-5 CM
MARCH
APRIL

3.4.3.1 Salinity

Changes in groundwater salinity were similar to those of the soilwater at the depth of the roots over this tide cycle. Greatest change in salinity occurs in near-surface soils during drying (Figure 11). Five days without seawater recharge (which is a conservative drying interval for these sites; see Figure 6) increased interstitial soil salinity by about 30 $^{0}/_{oo}$ in the upper 5 cm of the soil profile. Onset of recharge lowers the salt content as the concentrated and crystallized salts are diluted and re-dissolved. Salinity changes produced under variable wetting, however, are damped deeper in the profile so that soilwater salinity remains relatively stable within the main "root zone " throughout the tide cycle.

3.4.3.2 Chloride

Chloride concentrations were measured on the same soil samples as those used for salinity measurements. Changes in chloride concentration under variable recharge generally mirrored those of soil salinity, constituting about 70% of TDS.

Table 4. Soil properties for the landward mangal at King Bay, the tidally-restricted and unrestricted mangal truncated by the Cossack Causeway and the mangal fringing the shoreline at Cossack.

Site	Depth (cm)	pH (air-dry)	Particle Size Distn. Sand %	Silt %	Clay %	Texture	Soil* Moisture %	Soil* Salinity $^{0}/_{oo}$	Soil* Chlorinity $^{0}/_{oo}$	Organic Matter %	Munsell Soil Colour Code
King Bay	0-5	8.14 ± .03	74 ± 3	9 ± 0.7	17 ± 3	Sandy loam	22-46	64-128	68-106	4.28 ± .31	5 YR 4/2 Dark reddish grey
	10-20	7.06 ± .03	75 ± 6	8 ± 0	17 ± 0.7	"	30-46	58-72	39-54	3.52 ± .31	5 YR 4/1 Dark grey
	40	7.03 ± .01	73 ± 2	10 ± 1	17 ± 0.7	"	33-59	66-82	39-59	3.82 ± .01	5 YR 3/1 Very dark grey
Cossack (unrestricted)											
	0-5	7.78 ± .06	39 ± 3	25 ± 2	36 ± 2	Clay loam	19-64	64-280	38-236	8.13 ± .30	7.5 YR 5/4 Brown
	10-20	7.77 ± 0.4	46 ± 3	25 ± 1	29 ± 2	"	38-54	50-72	32-47	7.40 ± .50	"
	40	7.75 ± .02	47 ± 1	22 ± 2	31 ± 2	"	44-66	45-76	30-65	6.87 ± .46	"
Cossack (restricted)											
	0-5	8.32 ± .17	44 ± 4	18 ± 0	38 ± 4	Clay	20-52	70-410	52-312	8.20 ± .10	7.5 YR 5/4 Brown
	10-20	8.17 ± .08	46 ± 1	17 ± 0.7	37 ± 7	"	41-64	61-88	46-65	7.30 ± .30	"
	40	7.96 ± .03	49 ± 6	17 ± 0.7	35 ± 1	"	51-67	72-94	50-75	6.89 ± .27	"
Cossack town											
	0-5	7.48	72	9	19	Sandy loam	30-32	49-51	30	6.00	5 YR 4/4 Reddish brown
	10-20	7.61 ± .05	79 ± 3	9 ± 0.9	13 ± 3	"	31-32	45-49	26-32	6.05 ± .51	"
	40	7.73	84	6	10	"	47-51	45-48	30-34	5.36	"

* Neap - Spring Tide Cycle extremes 15th-30th March 1985; pH, particle size distribution and organic matter are means of 3 samples ± S.E.

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Figure 11. Influence of tidal exchange on depth to free water, groundwater salinity, soilwater salinity, soilwater chloride and soil moisture content over a tide cycle at King Bay. The amplitudes of predicted tides over the tide cycle are shown. Vertical dashed lines show the change from drying to wetting and wetting to drying phases of the cycle. The horizontal dashed line represents normal seawater salinity. All samples were collected at low tide. Soil properties were monitored at three depths: 0-5 cm, 10-20 cm and 40 cm. Ranges of duplicate samples are shown for each date. Where these are the same single points only are plotted. Soil salinity, chloride and moisture values are means of 3 subsamples from each sample (see text for standard errors).

3.4.3.3 Soil Moisture and the Water Table

Moisture contents of surface soils ranged from 22 to 46% (expressed on the basis of dry weight) over the tide cycle; those deeper down ranged from 30 up to 59% in these sandy loams (Figure 11; Table 4). Lowest values were recorded in surface soils (0-5 cm). Some of the surface values were higher after a few days drying and this may reflect some upward seepage of water. Changes in the depth of the water table over the tide cycle indicate that this is within 10 cm of the surface between wetting flood tides, and at the surface during inundation (the latter is not shown). After five days without tidal recharge the water table fell to about 60 cm below the surface, an average decrease of about 7 cm d^{-1}..

3.5 EFFECTS OF DISTURBANCE TO TIDAL EXCHANGE

Disturbance to tidal wetting introduced by road construction at Cossack causeway and at Pope's Nose Creek is shown schematically in Figure 12 A-E. In both cases the roads truncate the mangal perpendicular to the creeks so that wetting landward of the rock-fill roads depends on whether there is sufficient tidal penetration and duration to permit enough water to pass through the resistance and fill the creek before the tide turns and flow is reversed. This resistance to water flow introduces a temporal lag in the onset of wetting; the landward mangal is still filling when the tide turns and ebb flow begins to drain the seaward side (B). This produces a depth differential in the creek on each side of the road. When the water height on the seaward side falls below the level of the landward side the latter begins to drain, but this is also temporally-lagged because of the resistance offered by the road (C). The seaward side drains completely on ebb tide while the landward side still retains water and drains slowly (D). The arrival of the next flood tide increases water depth on the seaward side when the landward side is still emptying (E).

This sequence introduces two major changes to natural recharge and these have their greatest effect at different times of the year as a result of variable tidal amplitudes:

1. ponding of seawater landward of the road during the equinoxes (March,September); and

2. prolonged drying from reduced tidal wetting, particularly around the winter solstice (June,July).

3.5.1 WATER RETENTION

Retention of water occurs only on the tidally-restricted side of the road at Cossack and Pope's Nose Creek when the slowed ebb flow is hindered by incoming flood tides (Figure 12E). Tidal wetting each side of the road at Cossack is shown for tides approaching the March equinox in Figure 13. Two of the flood tides shown in Figure 13a are of sufficient magnitude to wet the seaward tidally-unrestricted site for about 100 minutes and 50 minutes, respectively (Figure 13a). Measured peaks in tidal wetting are in phase with the predicted times of high water. Water depth during inundation is close to 30 cm, which is somewhat higher than the height of the pneumatophores (negatively-geotropic breathing roots) of *Avicennia* here, but these breathing roots are not normally submerged for periods longer than about an hour.

On the tidally-restricted site a 5.1 m tide (predicted) wets the site and is effectively in phase with the natural tide cycle so that ebb flow is not impaired (Figure 13b). The duration of wetting, however, is prolonged. A 5.2 m tide (predicted) wets the disturbed site, and is followed by a succession of flood tides of sufficient magnitude to over-ride the slow drainage back through the road and small culverts on ebb tide. Successive flood tides of this magnitude or greater result in ponding of seawater as ebb flow rates are slowed. A large incoming flood tide, 5.5 m here, increases water depth rapidly; the subsequent drainage rate is partially governed by the magnitiude of the next flood tide. Thus water drained faster on 6 April than on 7 April, when ebb flow was interrupted by a flood tide of greater magnitude. These disturbances eventually result in the measured and predicted times of peak water height being out of phase (cf Figures 13a & 13b).

The remainder of the flooding period was not monitored. Magnitudes of the following successive flood tides were 5.3 m, 5.7 m, (8 April), 5.1 m, 5.6 m (9 April), 4.8 m 5.3 m (11 April) and, as predicted from tide tables, retention of water ceased on the 10 April, five days after it began. Chronic flooding of this type involves only a small percentage of the total annual flood tides (3% in 1985) and varies in intensity depending on tidal magnitudes. Thus water retention is most prolonged during the equinoxes, around March and September, when tides are largest, and is least prolonged around the time of the winter solstice, when tides are smallest (Figure 14).

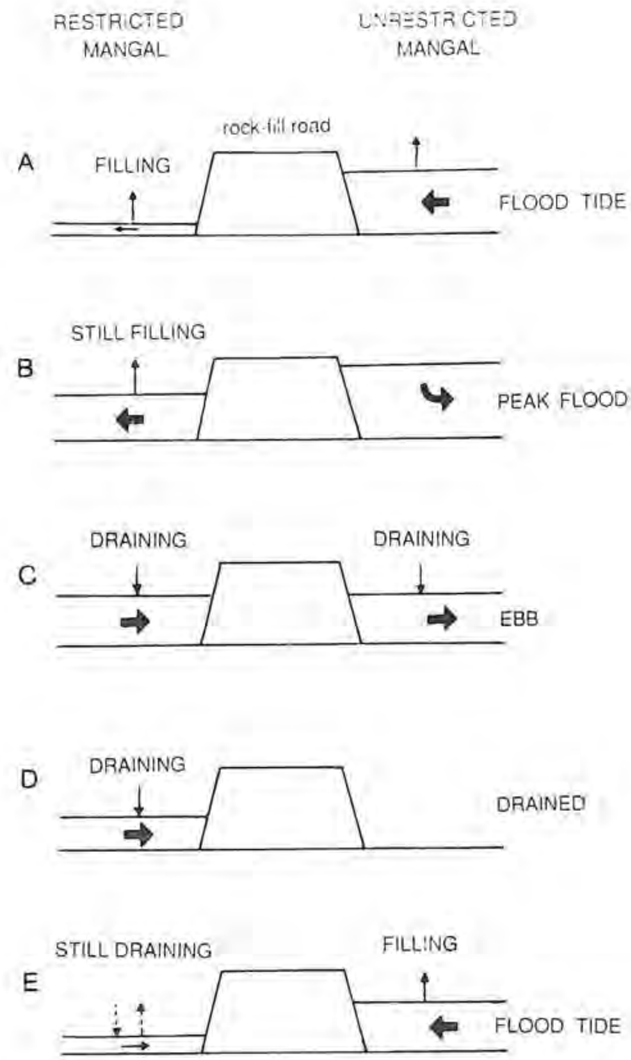

Figure 12. Resistance to water flow imposed by road construction. The sequence of events leading to restricted drainage is shown schematically in A-E (see Section 3.5).

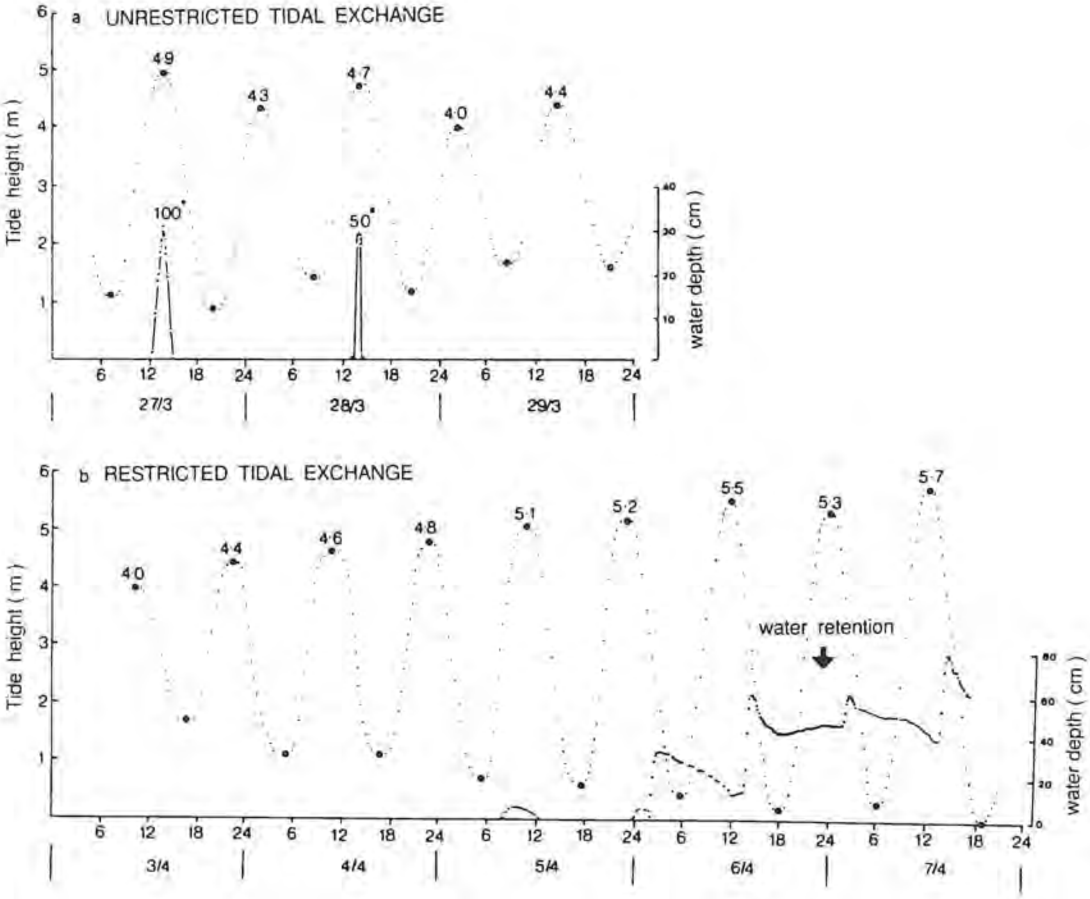

Figure 13. Duration of tidal wetting and water depths experienced during inundation a: in the tidally-unrestricted and b: in the tidally-restricted mangal on each side of the road at Cossack during the March-April equinox. Shown are 10-minute readings from data loggers buried in the mangrove soils. Duration of wetting in the tidally-unrestricted mangal is shown,in minutes, above each curve. Water retention is demonstrated in the tidally-restricted mangal as a result of resistance to drainage. Water depths on the restricted site correspond to the landward limit of remaining living trees. Superimposed on the logger outputs are predicted tides with the peak height indicated for each flood tide.

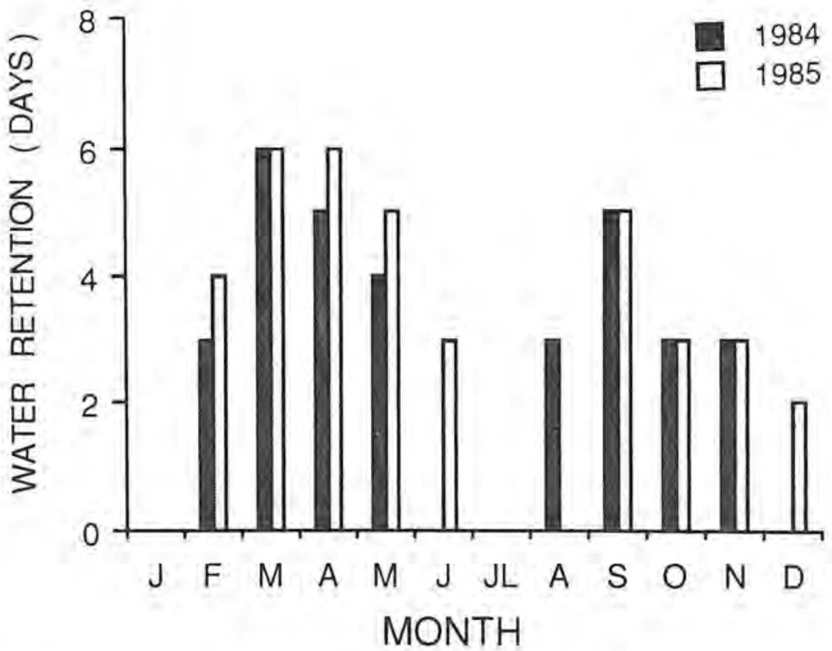

Figure 14. Seasonal occurrence and duration of seawater ponding caused by restricted tidal exchange at the Cossack causeway. Figures are based on field-calibration of predicted tides for 1984 and1985 (see Section 3.5.1).

3.5.2. ALTERED SOIL PROPERTIES

The influence of variable tidal recharge on several soil properties on each side of the causeway at Cossack are compared in Figures 15 and 16 to gauge the extent of changes introduced by the road. These data were collected in an identical manner and over the same days as those at King Bay (see Figure 11). Soil chloride has not been plotted for the Cossack sites but the results were similar to King Bay, with this ion constituting 70% of TDS (see Table 4 for ranges over the tide cycle). There were marked differences in salt concentrations of soils under living trees separated by the road. In the tidally-restricted mangal, groundwater salinity reached a maximum of 93 $^{0}/oo$ over this tide cycle. The maximum difference in groundwater under living trees on each side of the road on the same day was 34 $^{0}/oo$. Changes in soilwater salinity were greatest in surface soils (0-5 cm) during drying, increasing over four days without recharge by about 140 $^{0}/oo$ in the unrestricted and 100 $^{0}/oo$ in the tidally-restricted mangal (Figure 15). A further three days drying on the tidally-restricted site increased surface salinity to about 300 $^{0}/oo$. Onset of recharge rapidly lowered the salt concentration in this zone. The minimum salinities measured in these surface soils at low tide were all higher at the tidally- restricted site compared with the adjacent unrestricted mangal. Like the King Bay site, the influence of variable recharge on soil properties is damped with increasing soil depth. Marked differences in soilwater salinity are apparent, however, at the depth of the cable roots of living trees on each side of the road, with a mean difference of 26 $^{0}/oo$ and maximum difference of 41 $^{0}/oo$ over this tide cycle at a depth of 40 cm (Figure 15).

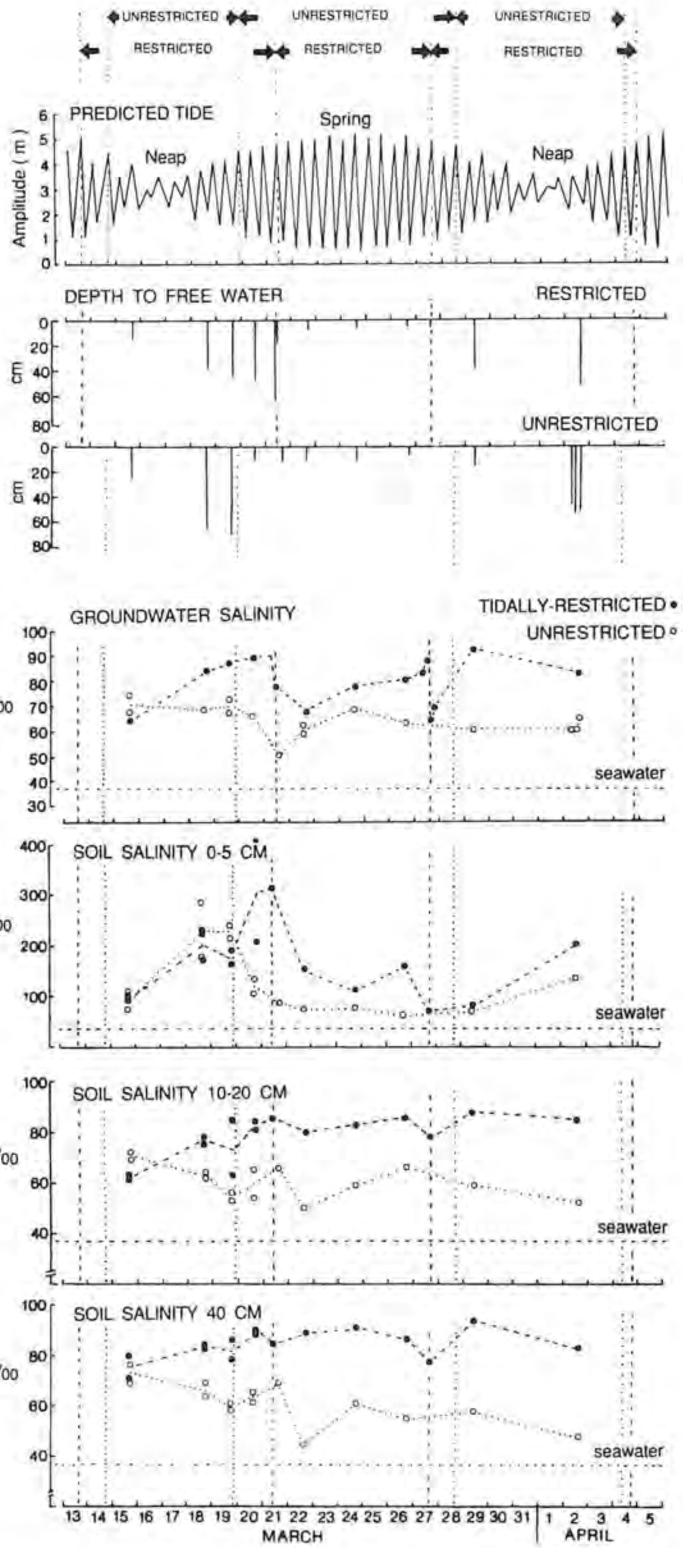

Figure 15. Influence of tidal exchange on depth to free water, groundwater salinity, and soilwater salinity on the tidally-restricted and unrestricted sides of the road at Cossack. Measurements taken at each site over the same tide cycle are superimposed. The amplitudes of predicted tides over the tide cycle are shown. Vertical dashed lines show the change from drying to wetting and wetting to drying phases of the cycle. The horizontal dashed line represents normal seawater salinity. All samples were collected at low tide. Soil properties were monitored at three depths: 0-5 cm, 10-20 cm and 40 cm. Ranges of duplicate samples are shown for each date. Single points only are plotted where these are the same. Soil salinity, chloride and moisture values are means of three subsamples from each sample (see Section 3.4.3).

The water table at Cossack behaved similarly to that at King Bay, being at the surface during inundation (not shown) and within 10 cm of the surface at low tide between wettings (Figure 15). There was little difference in the behaviour of the water table on each side of the road over the same tide cycle. It fell at similar rates to the King Bay site, from about 20 cm to 70 cm over five days of drying in the tidally-unrestricted mangal and from 10 to 50 cm in the tidally-restricted mangal over the same period (15 -19 March; Figure 15). Soil moisture contents, ranging from 19 to 67% of the dry weight (Figure 16), were slightly higher than those at King Bay. Drying out on neap tides was more noticeable in the upper layer of the profile in the clay soils at Cossack (Figure 16) compared with the sandy loams at King Bay (Figure 11), but the changes were damped further down the profile so that moisture contents (at low tide) were similar throughout the tide cycle at the depth of the cable roots irrespective of variable recharge at the surface.

On one occasion a comparison was made between the seaward and landward boundaries of the now-dead zone of mangroves at the Cossack causeway (Table 5). After a week without tidal recharge, salinities under the trees at the depth of the cable roots ranged from 83 to 130 $^0/_{00}$ across this zone, similar to the range measured across the zone of dead mangroves at the tidally-restricted Pope's Nose Creek site (Figure 8).

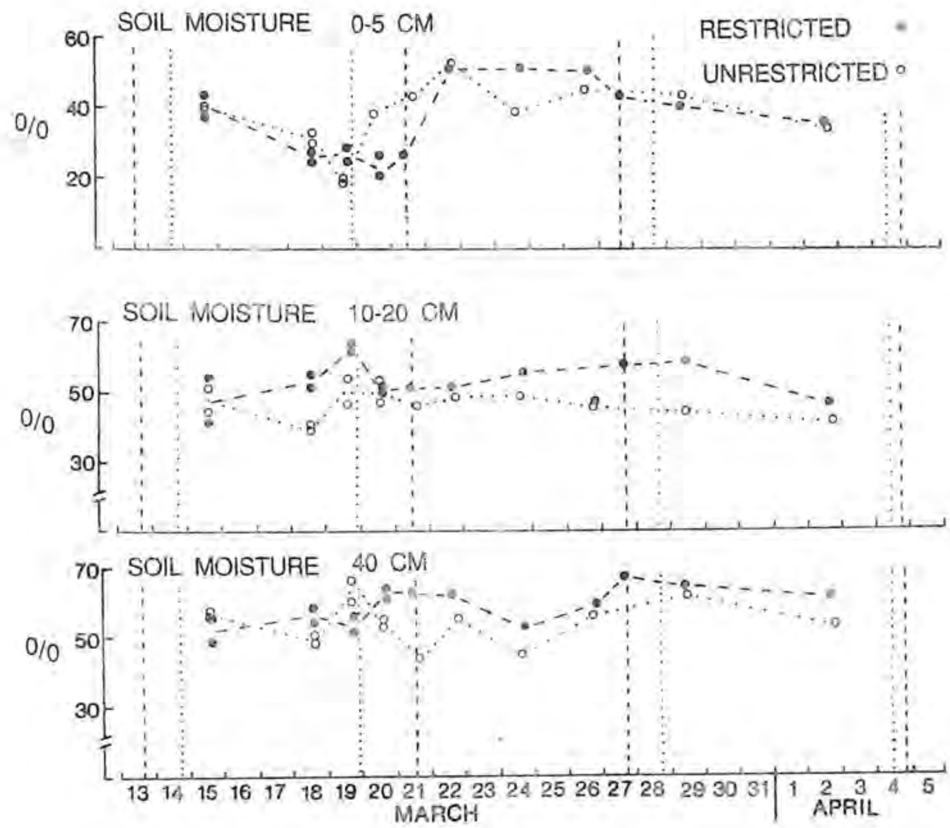

Figure 16. Influence of tidal exchange on soil moisture content (% of soil dry weight) in the mangal on each side of the road at Cossack. Measurements taken at each site over the one tide cycle are superimposed. Soils were monitored at three depths: 0-5 cm, 10-20 cm and 40 cm. Vertical dashed lines correspond to those shown in Figure 15 and depict the change from drying to wetting and wetting to drying phases of the tide cycle for each site. Ranges of duplicate samples are shown for each date. Where these are the same single points only are plotted. Each point is the mean of three subsamples from each sample (see section 3.4.3 for standard errors).

Table 5. Soil properties across the "dead zone" in the tidally-restricted mangal at Cossack, Western Australia. Data shown are for one day (20-3-1985) during the neap phase of the tide cycle at the seaward and extreme landward limit of now-dead trees.

Location	Days Since Last Recharged	Soil Depth (cm)	Soil Salinity (°/oo)	Soil Chloride (°/oo)	Soil Moisture (%)	Depth to Water Table (cm)
Seaward limit of dead mangal						
	7	0-5	300	220	24	48
		10-20	83	56	52	
		40	88	67	62	
Landward limit of dead mangal						
	8	0-5	220	165	38	47
		10-20	130	100	43	
		40	129	93	49	

4. DISCUSSION

Mangroves occupy about 2400 km² of the Western Australian mainland and islands to 1 km offshore (Galloway 1982). Those surveyed here make up less than 3% of that figure, and about 12% of the mangals occurring along the arid north-west coast of Australia, extending from North-West Cape to Cape Keraudren. Over and above their aesthetic value, introducing attractive green forest to an otherwise desolate coastline, they are important refuges for the biota, particularly birds and fish, which use the mangals as nursery areas, for breeding and as a source of food (Semeniuk, Kenneally and Wilson 1978; Kenneally 1982). They also act as physical barriers to storm surge and erosion on a coastline where low wave energy and large tidal amplitudes dominate, and which is subjected to seasonal, but severe, cyclonic activity (Lourensz 1981).

4.1 TIDAL RECHARGE AND SALINITY

In the arid mangrove environment of north-west Australia, constraints placed on the plants' ability to extract water can be large and will tend to exacerbate stress, particularly where variable (often high) salinity and tidal recharge can change the soil water status in conjunction with high evaporation rates and high temperature. Mechanisms available for marine and freshwater recharge to the mangals in this region have been summarized by Semeniuk (1983; 1985) and include daily, fortnightly and monthly seawater inundation (the frequency depending on the location up the gradient of the tidal mud flat), perennial seepage from the hinterland and seasonally-dependent seepage and freshwater runoff arising from sporadic cyclonic rainfall. These papers emphasise the strong dependence of available recharge mechanisms, particularly freshwater seepage, on the local stratigraphy, where the tidal mud flats contact other stratigraphic units, and the importance of freshwater sources in producing low-salinity groundwater to support mangroves at the landward, hinterland fringe of the mangals. In the arid Pilbara the nature of the available recharge mechanisms results in limited freshwater seepage and this precludes development of distinct mangrove zonation at the hinterland margins of the mangals as occurs in more humid, higher rainfall locations further north (Semeniuk 1983).

Groundwater salinities under unvegetated salt flats visited for this study were spatially-variable, but temporally quite stable, never attaining low values for long intervals, irrespective of recharge by seawater. This situation may also occur during freshwater recharge, as Semeniuk (1983) has noted that rain falling on salt flats during the wet season does not necessarily infiltrate directly but may act in the same manner as ebbing seawater, a large portion flowing off the surface. Lateral movement of groundwater under the tidal flats is probably very slow compared to surface flow (and in some cases, because of the nature of the aquifer, the groundwater is locked-off), so that temporal changes in groundwater salinity under the influence of variable recharge appear to be localized, temporary phenomena. In contrast to soils of the salt flats, those of the vegetation zone are more strongly bioturbated, more frequently wetted and therefore offer less resistance to infiltration and percolation of tidally-driven seawater (or rainfall). Hypersaline groundwater located close to the surface can thus be readily diluted. This, however, is also temporary, and the hypersaline conditions are re-established quickly. Some of the burrowing crustaceans, fish and molluscs are present at high densities (LeProvost, Semeniuk & Chalmer 1980) and probably have an important role in regulating the water supplied to the roots of the trees, but this has never been quantified here.

Whether the short periods over which salts are diluted during wetting in shallow, bioturbated soils (Figure 10) imparts any benefit to the mangroves by reducing salt intake during water uptake is not clear. Photosynthetic performance (net productivity) of mangroves may be reduced with increasing salinity (Hicks & Burns 1975) and transpiration rates can change rapidly in response to inundation (Lewis & Naidoo 1970) suggesting that the trees react sensitively and quickly to changing soil properties. In view of the shallow water table, mangroves here are probably phreatophytic and the benefits of any temporary dilution of salts which occurs near the surface during wetting will depend on whether the roots involved in water uptake are concentrated within this zone. Cable roots of *Avicennia* at sites visited in this study were typically found within 30 to 40 cm of the surface where soils are often saturated during tidal wetting. The extent to which these or finer roots are involved in water uptake and ramify in these muddy sediments is not yet known as careful, deep excavations of the root system have never been performed. Recent laboratory experiments, however, suggest that salt and water are transported inwards largely via the symplast, and at the distal, younger portions of third and fourth-order roots, at least for young *Avicennia marina* plants reared in dilute (25%) seawater (Moon, Clough, Peterson & Allaway 1986).

Although laboratory studies indicate that *Avicennia* generally grows better in dilute seawater rather than in freshwater or at oceanic salinity (Clarke & Hannon 1970; Burchett, Field and Pulkownik 1984; Clough 1984), there are obviously wide differences within the same species in the capacity to function at high salinity. For example, Clarke and Hannon (1970) report no survival of *Avicennia marina* grown at twice seawater salinity for three months in laboratory trials, yet the same species can survive in locations here at salinities far-exceeding this limit, albeit as rather depauperate trees. The effects of hypersaline conditions on photosynthesis and growth of mature trees in this region are not known but the thresholds may be quite different to those reported for young plants reared artificially at salinities up to seawater concentration. The physical appearance of moribund trees in this study was similar to that described by Lugo, Cintron & Goenaga (1981) under the influence of hypersalinity, with yellowing, deformation and reduction in the surface area of leaves.

All examples of stressed and dead mangroves observed here were situated at, or close to, the extreme landward limit of the vegetation, where natural salinity values already exceed, by two-fold, those typical of mangals fringing the seashore. Salinity in these locations is thus readily extended beyond acceptable concentrations by disturbances such as road construction which reduce the opportunity for dilution of salts during seawater inundation, especially where the soils naturally develop extreme salinities in the upper layer of the soil profile in the absence of tidal wetting (Figures 11 & 15). The groundwater salinities measured under dead and dying mangroves, from 92 to 156 $^{0}/_{00}$ (Table 3 and Figure 8) are not characteristic of soils under living mangals at this latitude where groundwater salinity associated with living trees rarely exceeds 90 $^{0}/_{00}$ (Semeniuk 1983;

1985; this study). This upper threshold appears to be quite consistent for arid mangroves generally (MacNae 1968; Cintron, Lugo, Pool and Morris 1978). Johannes (1982) has reported moribund and dead *Avicennia marina* at Mangrove Bay, about 400 km south of the present study area, at salinities ranging from 84 to 102 $^0/_{00}$. Mortality was not associated with any physical restriction to tidal-exchange and was considered to have resulted from elevated salinity brought about by several years of below-average rainfall. Johannes considers the decline to be reversible, consistent with the original proposal of Cintron *et al* (1978) whereby natural expansion and contraction (mortality) of these communities in arid environments occurs naturally in response to cyclic changes in climate. The localized death of mature, recumbent *Avicennia* at the landward, tidally-unrestricted site at Levee 24 (Figure 3c), is unlikely, however, to have arisen from any natural fluctuations in the salinity gradient. There is evidence that the ion ratios in the groundwater here are disturbed (Paling 1983), suggesting that there may have been an influence of the adjacent salt bitterns pond. The gradient of the mud flat next to the wall of the bitterns pond, however, also appears to be disturbed, as ebbing seawater becomes ponded here. Evaporation of this residual water could alternatively explain the extreme salinities measured under the now-dead, but mature mangroves near the wall.

4.2 SOIL PROPERTIES

Differences in composition and physico-chemical properties of mangrove soils at the three quite separate locations examined for this study reflect differences in several factors such as local stratigraphy, sedimentation, drainage patterns, vegetation type and structure. A detailed examination of soils was not the purpose of this study and the data collected are too site-selective to make generalizations about the nature of the mangrove soils of this region. Nevertheless they can be quite usefully compared with similar records collected from studies of soils from other mangrove systems. Naidoo and Raiman (1982) compared several mangrove soils with non-mangrove soils from the same region in South Africa and noted, among other properties, higher clay, organic content and cation exchange capacity (CEC) in the mangrove soils. Those surveyed here, in comparison, were slightly more basic and with a higher organic matter content at equivalent depth, the latter suggesting an important contribution from litter. Although CEC was not examined for this study it is probably high at the Cossack road sites, which are clays with a high content of organic matter (Table 4).

Soils from the landward King Bay site and the seashore at Cossack are quartz sands containing shell fragments and resemble the coarse sandy soils described for mangroves of the Sydney district by Clarke and Hannon (1967), although the silt and clay contents are somewhat higher, at 10 and 20% respectively. The landward Cossack road sites are fine clays and resemble the clay muds which have been described from mangrove systems in other parts of the world (see Naidoo 1980 and references cited therein; Naidoo and Raiman 1982).

4.3 DISTURBANCE AND STRESS

Mangroves are generally perceived as being stress resistant by virtue of their salty often waterlogged habitat. Levitt (1980) has usefully divided stress resistant plants into three groups- those which are stress tolerant but not stress avoiding, those which are stress tolerant and stress avoiding, and those which are stress avoiding but not stress tolerant. Mangroves appear to fit best into the second group. They display several morphological and physiological adaptations which enable them to survive and grow in the intertidal environment including specialised roots modified to enhance gas exchange with the atmosphere (pneumatophores), selective pathways located at the root for filtering salt taken in during water uptake (Scholander 1968; Moon *et al* 1986), salt-secreting glands in the leaf and electro-chemical barriers in the cytosol to counter high internal salt levels (osmoregulation). Some of these features are suggestive of avoidance mechanisms (eg. extrusion of salt via glands and salt filters in the root) while others suggest tolerance (ion accumulation in leaves and osmoregulation via compatible solutes). Strictly, true stresses operate only if otherwise useful energy is diverted from normal cell function to maintain the status quo (Ivanovici & Wiebe, 1981) and this raises the question as to how well these plants are able to cope with pressures over and above the natural ones, for example the effects of disturbed tidal exchange on the water extracting capacity of the trees under normally hypersaline conditions in this climate.

Examples of the types of disturbance to mangrove communities of the Dampier-Cossack region resemble those reported for mangrove communities elsewhere in Australia and overseas, with loss and degradation following smothering from dredge-spoil dumping and altered drainage imposed through bunding, particularly from road construction (Hegerl & Davie 1977; Bird & Barson 1982; Hegerl 1982; Patterson Zucca 1982; Saenger, Hegerl & Davie 1983). By world standards the impact of disturbances on the Pilbara mangroves is still relatively minor, because, unlike some other tropical mangrove communities, there is so far no large-scale commercial exploitation of this natural resource for silviculture or for fisheries (cf Saenger *et al* 1983). Further, as noted by Saenger (1985), the mangrove communities here are not under threat from a population at subsistence level, such as occurs in Africa and Asia. This, however, does not argue for complacency with regard to their future. Despite their recognized conservation value and the numerous Australian and overseas case studies documenting the deleterious effects of urban development and commercial projects centred on mangrove communities (Saenger *et al* 1983; Hamilton & Snedaker 1984), there is not yet broad-scale legislation available here to fully-protect, regulate and manage activities in these communities. This goal has been hampered ,in part, because of their location, at the interface between land and sea, which brings them under the jurisdiction of several administrative bodies (Saenger *et al* 1983).

4.3.1 EFFECTS OF ROAD CONSTRUCTION ON TIDAL EXCHANGE

Despite the recognized importance of freshwater sources to mangrove communities, a large proportion of the water supplied to the Pilbara mangroves is met from seawater recharge because freshwater input is limited and rainfall sporadic and highly seasonal. The disturbances to normal drainage of water imposed by the roads here has therefore probably had greater impact on the supply of marine rather than fresh water to the trees, and this is borne out by the lack of any large-scale loss or deterioration of mangroves seaward of the roads, where these have truncated sections of the mangals and reduced tidal exchange. The very visible loss of mangroves with reduced tidal exchange here, however, can also occur if freshwater sources are diverted or cut-off following bunding of tidal creeks (Hegerl & Davie 1977; Saenger *et al* 1983) An important feature of inadequate water exchange in relation to roads in this region is not only the reduction in the amount of water able to pass under the roads during inundation but the quality of the flow. Normal sheet flow of tidal waters was considerably modified in some cases so that seawater exchange was reduced to fast, concentrated flow through inadequate culverts with resulting erosion and channelling of water into discrete pathways, diverting around some of the trees. A secondary, but positive, feature of the causeways truncating mangals in this study, however, is colonization of some of the road verges and tidal flats immediately next to the road on the tidally-restricted side by new and healthy *Avicennia*, presumably benefiting from improved rainfall run-off and subsequent reduction in salinity.

Exchange of marine water has been restricted in the zone of moribund and dead mangals for at least 10 years at Cossack (based on information available on the final completion dates for the present road) and probably for 15 years at Pope's Nose Creek. The most likely causes for the widespread death of mangroves landward of the road at these sites is from the combined effect of increased salinity, resulting from prolonged intervals without tidal recharge, particularly around the winter solstice (June and July), and retention of ebbing seawater during equinoctial tidal flushing (March and September), during which ponding is sufficient to submerge pneumatophores for days rather than the normal duration of one or two hours. At Cossack, drying of soils in the absence of recharge has been extended by at least two-fold under the remaining living trees, and water is ponded for up to six successive days (Figures 6 & 14). These figures are based on comparisons between the magnitudes of flood tides wetting healthy trees on the unrestricted side of the road and those wetting the few remaining viable trees located at the margin of the dead zone in the adjacent tidally-restricted mangal and so provide a crude indication of the tolerance limits of the trees to this disturbance.

Increased salt around the roots during drying (Figure 15). is likely to be exacerbated in a region where rainfall is almost an order of magnitude lower than evaporation (Figure 1). Differences in salt content of soils at the landward and seaward margins of the dead zone landward of the road at Cossack (Table 5) reflect the magnitude of changes introduced by the road. A week without recharge probably indicates the maximum soil salinities encountered across this zone. The range, 83 to 130 ^{0}/oo, at the depth of the cable roots, is mostly well above the reported tolerance limit of these trees. Assuming that the maximum soil salinity measured under living trees in this study reflects the upper threshold for their survival and that the salinity range measured in the adjacent healthy mangal seaward of the road at Cossack accurately reflects the original state of the now dead mangroves, then the disturbance introduced by the road has apparently increased salinity by at least 20 ^{0}/oo at the seaward end of the dead zone next to the road, and up to 50 ^{0}/oo at the extreme landward margin of the original, but now dead vegetation zone.

It cannot be clearly established from the information available whether widespread death of mangroves associated with roads in this region has occurred rapidly or gradually. Ponding of seawater would affect the entire stand simultaneously irrespective of the location of trees up the gradient of the tidal flat, while death from prolonged drying would affect the extreme landward limit of the vegetation first where salinity is already high due to naturally-long intervals without seawater recharge. Over the long term, both water retention and reduced tidal wetting would tend to increase salinity. Moreover, this increase in salt would be enhanced by intermittent ponding of seawater, such as occurs at the Cossack causeway, rather than if ponding were a permanent feature of tidal-restriction (Clarke & Hannon 1970). Subjecting mangroves to different periods of waterlogging(and salinity concentrations (though not exceeding seawater salinity) under controlled conditions in the glasshouse produces marked physiological responses at the level of the leaf (Naidoo 1983; 1985) and the root (Burchett *et al.* 1984), including increased stomatal resistance (implying reduced photosynthesis), lowered leaf water potentials (exacerbated by longer periods of flooding), swelling of the chloroplast membranes when waterlogging is prolonged, albeit over longer periods than occurs here in the disturbed mangal, and decreased oxygen consumption by the roots. The individual contribution of these stressors to mangrove mortality at Cossack is difficult to assess and complicated here because these have their greatest impact at different times of the year. It is likely that some of the physiological effects described above were also manifested here under the influence of waterlogging and increased salinity, however, it remains to be seen to what extent the mangroves growing under normally hypersaline conditions adapt to this type of disturbance. Despite the short time seawater is ponded at Cossack, the reulting flooding has potentially-damaging effects on the root system of the trees by increasing the diffusion-resistance to gas exchange and reducing soil aeration (Naidoo 1985). Excavation of cable roots of moribund and dead *Avicennia* in the tidally-restricted mangal frequently revealed partially-rotted roots associated with waterlogged and anoxic tissue. These are similar symptoms to those described following mass-mortality of mangroves caused by freshwater-flooding of an estuary following its closure (Breen & Hill 1969). Flooding in some cases can also introduce secondary problems resulting in death of mangroves when they become asphyxiated by silts carried in the flood waters and deposited on the trees (Watson 1928; Hegerl 1975) This type of loss has also been noted from this region, for example at the mouth of the DeGrey River following severe cyclones (Nicholson, pers. comm.).

Noticeable differences in the silt : clay ratio of soils separated by the road at Cossack (Table 4) suggest some influence of bunding on the particle size distribution of the soils here. Diversion and canalization of rivers have been linked to changes in the silt and clay contents and CEC in mangrove soils where deposition of sediments are altered under reduced inundation (Naidoo and Raiman 1982). The textural differences each side of the road at Cossack, however, are not just confined to the surface layer, but are present at least to half a metre depth which would suggest that if they are related to tidal restriction caused by the road then there has been considerable reworking of the surface deposits over the decade since the site was first disturbed. Possible differences in sediment deposition occuring during the study on each side of the road were tested crudely here by inserting calibrated marker pegs at approximately 10 m intervals through the mangal on each side of the road and measuring heights relative to datum on four occassions over a year. No significant differences were found between the sites separated by the road though there were small changes detected in the beds of the erosion-channels in the tidally-disturbed mangal where energy of water flowing is most concentrated. It may be rather optimistic, however, to expect measurable differences in sediment deposition over such a short sampling period, especially considering the long time over which this mangal has been tidally-restricted.

5. CONCLUSIONS

This study illustrates how the mangrove communities in this arid region are susceptible to man-induced disturbance especially where this interferes with the normal wetting regime of the trees. Natural changes in soil properties arising from variable tidal wetting and drying in the hypersaline landward zone of mangals are largest close to the soil surface and reduce with depth so that the salt content of the main groundwater field over the tide cycle remains temporally-stable at the depth of the main roots irrespective of tidal recharge at the surface. Short-term dilution of salts under the trees at landward infrequently wetted sites is achieved only temporarily and close to the surface during tidal wetting after which hypersalinity is rapidly re-established. Restricted tidal exchange tends to increase groundwater salinity beyond the survival threshold of the mangroves and also alters the natural frequency and duration over which their specialized root systems are immersed in seawater. Given the wide variety of disturbances to mangrove communities already present in this region there is a need to establish the extent to which they are able to adjust to man-induced perturbations, particularly where these modify the water supply to the trees. From the standpoint of the future survival of mangroves under threat from development the importance of maintaining the natural exchange of seawater needs to be emphasised since even localized changes to the amount and nature of water flow can have deleterious effects on these communities well removed from the source of the initial disturbance.

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