Coastal Education & Research Foundation, Inc.

Predicting the Effect of Sea-Level Rise on Mangroves in Northwestern Australia
Author(s): V. Semeniuk
Source: *Journal of Coastal Research*, Vol. 10, No. 4 (Autumn, 1994), pp. 1050-1076
Published by: Coastal Education & Research Foundation, Inc.
Stable URL: http://www.jstor.org/stable/4298296
Accessed: 28/12/2009 01:31

Your use of the JSTOR archive indicates your acceptance of JSTOR's Terms and Conditions of Use, available at http://www.jstor.org/page/info/about/policies/terms.jsp. JSTOR's Terms and Conditions of Use provides, in part, that unless you have obtained prior permission, you may not download an entire issue of a journal or multiple copies of articles, and you may use content in the JSTOR archive only for your personal, non-commercial use.

Please contact the publisher regarding any further use of this work. Publisher contact information may be obtained at http://www.jstor.org/action/showPublisher?publisherCode=cerf.

Each copy of any part of a JSTOR transmission must contain the same copyright notice that appears on the screen or printed page of such transmission.

JSTOR is a not-for-profit service that helps scholars, researchers, and students discover, use, and build upon a wide range of content in a trusted digital archive. We use information technology and tools to increase productivity and facilitate new forms of scholarship. For more information about JSTOR, please contact support@jstor.org.

Coastal Education & Research Foundation, Inc. is collaborating with JSTOR to digitize, preserve and extend access to *Journal of Coastal Research.*

http://www.jstor.org

Journal of Coastal Research	10	4	1050–1076	Fort Lauderdale, Florida	Fall 1994

Predicting the Effect of Sea-level Rise on Mangroves in Northwestern Australia

V. Semeniuk

21 Glenmere Road
Warwick, Western Australia 6024
Australia

ABSTRACT

SEMENIUK, V., 1994. Predicting the effect of sea-level rise on mangroves in northwestern Australia. *Journal of Coastal Research,* 10(4), 1050–1076. Fort Lauderdale (Florida), ISSN 0749-0208.

The patterns of mangrove distribution in tropical northwestern Australia are related to coastal dynamics, habitats and salinity. They also respond to the sedimentology of the tidal flats that back them, to coastal (sheet) erosion, and to the effects of some industrial impacts. These patterns provide information useful in predicting the variable effects of sea-level rise on mangroves. For instance, fundamental changes to soil regimes and salinity can be expected as tidal flat surfaces and groundwaters sedimentologically and hydrologically adjust to new levels of wave base and frequency of inundation as sea-level rises. Since mangrove assemblages and their zones are closely related to shore profile, soils, habitat stratigraphy and salinity fields, any change in these can lead to alteration of the structure and composition of mangrove systems.

The mangrove response to a rising sea level will depend on the environmental setting of the mangrove system. This includes the relative geomorphic and sedimentologic homogeneity of the coast, its tidal range, its stability, and the history of Holocene sea levels in regard to development of coastal gradients and the climatic setting which determines the variety of species that will respond to this Holocene sea-level rise and the type of reproduction the mangroves will utilise to keep pace with encroaching seas. A dichotomous key is presented which suggests that the response of mangrove coasts to a rising sea level will be quite varied from coastal sector to sector and even from site to site within a single coastal sector and climate setting.

Some case studies illustrate the probable effect of rising sea level on mangrove systems in Western Australia. The macrotidal shores of King Sound, a relatively simple coast in terms of habitat and stratigraphy, is eroding naturally by creek and cliff erosion and by sheet erosion progressing at 1–3 cm/yr. This erosion specifically simulates the effects of a rising sea. With coastal retreat, the mangroves are migrating landwards, generally keeping pace with the retreat. Mangroves colonise by seedling recruitment on the new substrates that become available through the processes of erosion, inundation, and dilution of hypersaline groundwater of the salt flats. As erosion and progressive dilution of hypersalinity proceeds, each zone within the mangrove belt displaces the adjoining one. Thus, sea-level rise in a system like King Sound would most likely result in the migration of mangroves, with similar composition and structure, into habitats made available by increased inundation. In arid zones, however, where mangrove population is maintained by vegetative reproduction, sheet erosion of tidal flats also causes landward migration of zones, but the individual zones keeps pace with a relative rising sea level by vegetative processes. Elsewhere in NW Australia, various mangroves assemblages with different composition, structure and population maintenance have developed along highly indented (ria) shores, in a heterogeneous suite of habitats that have evolved over the late Holocene. These habitats are defined by their geomorphic setting, sedimentologic processes, stratigraphic evolution, and ground water dynamics, and each is related to a specific height in relationship to sea level. A sea-level rise would inundate the various geomorphic/habitat systems, dislocating their suite in relation to the formative sea level. It is likely that these mangroves would not adjust as rapidly as the more homogeneous systems, and hence be disrupted.

ADDITIONAL INDEX WORDS: *Mangroves, sea-level rise, Northwestern Australia, tidal flats.*

INTRODUCTION

With the on-going increase in the content of carbon dioxide and other gases in the atmosphere, greenhouse effects on the globe are predicted to be variable. They include: higher temperatures of air and oceans, changes in rainfall in some regions, changes in wind regimes, increased storminess and incidence of cyclones, changes in evapo-transpiration and a rise in sea level due to thermal expansion of oceans and partial melting of ice sheets, snow fields and glaciers (PEARMAN, 1988).

It may be anticipated that the impact of greenhouse effects on mangroves (= mangals of MACNAE 1968) also would be manifold. It would involve direct effects such as increased temperature and carbon dioxide concentration on mangrove photosynthesis and physiology. This would alter their productivity at the local scale. Indirect effects would include stresses associated with a general sea-level rise, increased evaporation of soil water, and increased incidence of storms and cyclones. Increased storminess has direct impacts such as destruction of mangrove populations and indirect impacts such as the alteration of coastal geomorphology and habitats.

94017 received and accepted in revision 20 February 1994.

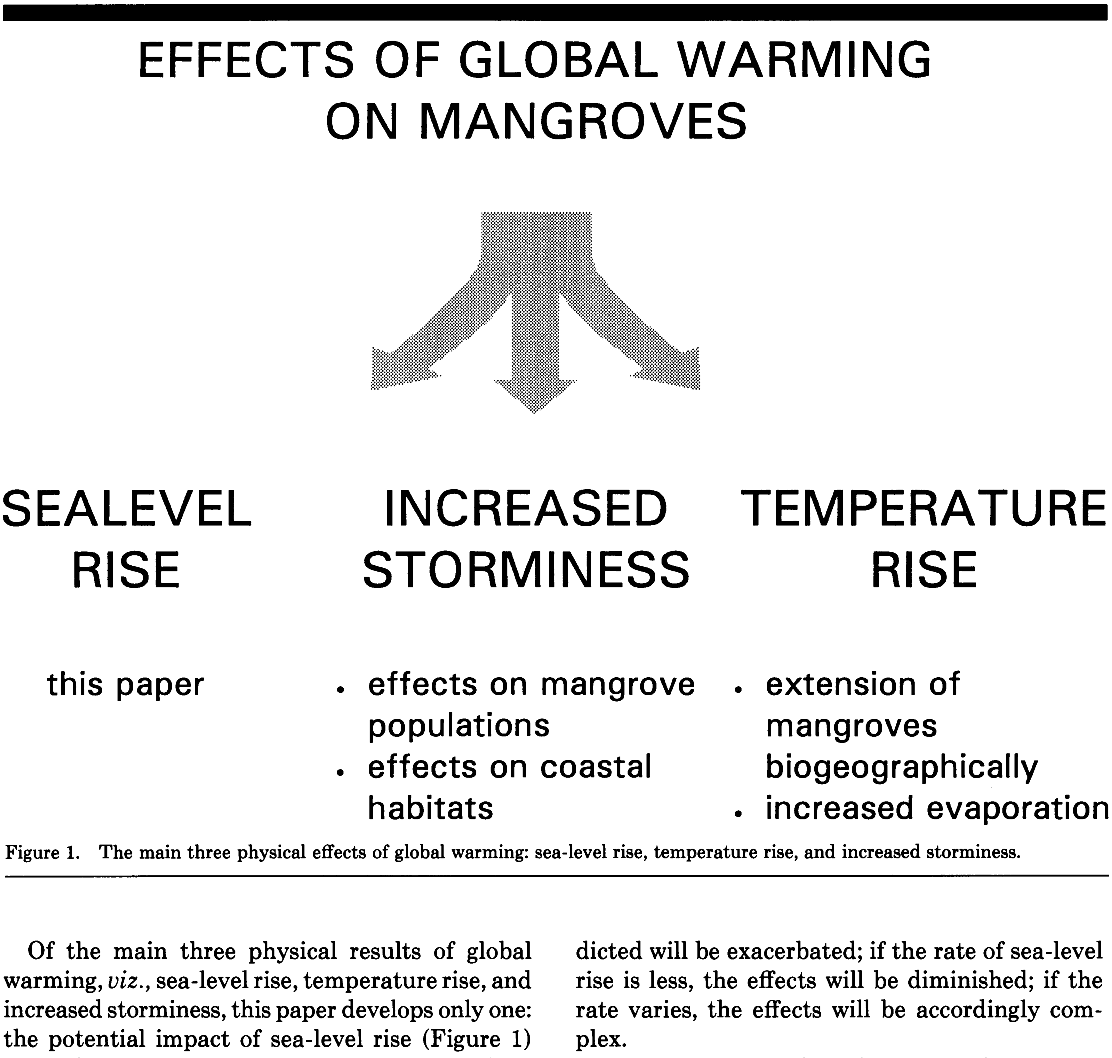


Figure 1. The main three physical effects of global warming: sea-level rise, temperature rise, and increased storminess.

Of the main three physical results of global warming, *viz.*, sea-level rise, temperature rise, and increased storminess, this paper develops only one: the potential impact of sea-level rise (Figure 1) using the mangrove systems of northwestern Australia as a case study. It is accepted, however, that the overall response of global warming on mangroves will be a result of all the effects acting synergistically. A projected global sea-level rise of some 1 mm per year (Gornitz *et al.*, 1982; Hoffman, 1984; Bird, 1988), culminating in a net rise of 0.5 m by the year 2045 is used in this paper. Recently, Daniels *et al.* (1992) have revised the expected rate of sea-level rise and deduce a lower rate than previous studies. It is not the intention of this paper to review the varying conclusions on the rate of expected sea-level rise, rather it is to present a model of mangrove response to rising sea levels within a complex system as occurs in northwestern Australia. If the rate of sea-level rise is greater than anticipated here, the effects predicted will be exacerbated; if the rate of sea-level rise is less, the effects will be diminished; if the rate varies, the effects will be accordingly complex.

Extrapolations and predictions of the effect of sea-level rise on tidal wetlands and in particular on mangroves and marshlands, have been presented by Orson *et al.* (1985), Bird (1988), Vanderzee (1988) and Parkinson *et al.* (1994). However, these models have been based on mangrove and marshland coasts that are rather simple. That is, the physiographic setting is generally of low energy and low gradient carbonate or peat swamps with little terrigenous sediment imput; the floristics and physiognomy/structure of the vegetation are relatively uncomplicated (*e.g.*, the Florida Coast; Davis, 1940; Spackman *et al.*, 1964; Lugo and Snedaker, 1974; Hine *et al.*, 1988; Parkinson, 1989). The examples of tidal wetland response to a rising sea level to date presented in the studies cited above is one of the encroachment of mangrove and marshland vegetation landwards as sea-level rises (SCHOLL, 1964; SCHOLL and STUIVER, 1967; BIRD, 1988). However, at a larger scale, *i.e.*, beyond the scale at which most of the studies cited above were carried out, coasts are heterogeneous in their processes and geomorphic and sedimentologic products. This would imply that the global response of mangrove systems to a sea-level rise also will be heterogeneous.

The region of northwestern Australia provides a range of excellent case studies and models of the potential variable response of mangroves to a rising sea level. The mangrove systems of northwestern Australia: occupy the coastal tract over a sub-continental sized area; exhibit much variability and heterogeneity (there are up to seventeen species of mangrove in the humid regions and one to four species in the arid regions); show a complex of physiognomic and structural types of mangrove vegetation (SEMENIUK, 1993b; SEMENIUK *et al.*, 1978; SEMENIUK and WURM, 1987); utilise a variety of propagation strategies; and display considerable complexity on the large scale as the coast crosses various geological provinces and climatic zones. Thus, the northwestern Australian coast and the habitats it provides for mangroves is heterogeneous with respect to processes and coastal products from sub-continental scale to small scale (SEMENIUK, 1986). Given this heterogeneity, it may be anticipated that the response of mangroves to a sea-level rise will not be simple and uniform, but will be variable. A single model cannot be established to predict a continent-wide response.

This paper explores the potential response of mangroves to an anticipated sea-level rise within this sub-continental scale setting. In particular, it emphasises that mangrove ecology is closely linked to coastal processes, geomorphic coastal setting, sedimentological processes, and groundwater hydrology. These factors are especially important in mangrove population maintenance processes at the local scale and the development and maintenance of mangrove habitats at the regional to local scale. Consequently, global greenhouse effects and sea-level rise will impact at various scales on a range of physical and chemical determinants of the mangrove systems and will have variable responses along the coast. For instance, a small rise in sea level at one location, where the coast is depositionally active, may have profound effects on the mangrove system—not directly on the mangrove vegetation itself, but on the patterns of sedimentation, which in turn will affect the mangroves. A similar rise in sea level at a second location may directly affect the mangrove vegetation itself by inundating and drowning mangroves inhabiting a barred lagoon. A small sea-level rise at a third location in a humid setting may result merely in the slow migration of the mangroves up the tidal flat slope, pacing the encroaching sea. Finally at a fourth location, but in an arid setting, the same sea level rise may result in the slow drowning and death of mangroves because the populations cannot reproduce fast enough.

The approach adopted in this paper to predict the potential effects of a sea-level rise on mangroves has been two-fold: (1) to document the dynamics of the geomorphologic, sedimentologic, and hydrologic setting of the coasts, and the population dynamics of mangroves systems in the various climatic and habitat settings, and (2) to use case studies of natural responses and industrial impacts that simulate a sea-level rise in this region. The former approach provides a baseline of the dynamics of the variable coastal systems. This baseline, if understood in sufficient detail, can provide an insight into mangrove responses if one of the parameters of the baseline (*i.e.*, sea-level) should change.

THE MANGROVES OF WESTERN AUSTRALIA—AN OVERVIEW

Mangroves occupy extensive coastal tracts of the tropical part of Western Australia (Figure 2a). They span a climatic gradient from arid in the south to humid in the north (BUREAU OF METEOROLOGY, 1975; GENTILLI, 1971, 1972; and Figure 2b) and occur in a wide range of settings and habitats (SEMENIUK, 1983, 1985, 1986, 1993b). They occur in tidal regimes from microtidal (<2 m) in the south to macrotidal (11.0 m) in the north (EASTON, 1970; DAVIES, 1977; and Figure 2c), inhabiting the interval between mean sea level (MSL) and about mean high water spring tide (MHWS) in arid to semi-arid environments, and extending almost up the position of equinoctial high water (EHW) in more humid climates. They inhabit coasts located in quite variable geological and geomorphic settings (Figure 2d), and hence occupy ria shores, tidal embayments, limestone barrier coasts, wave-dominated deltas, tide-dominated deltas, and beach/dune shores, etc. They occur along coasts that are variable both in their Holocene sea level history and in their modern

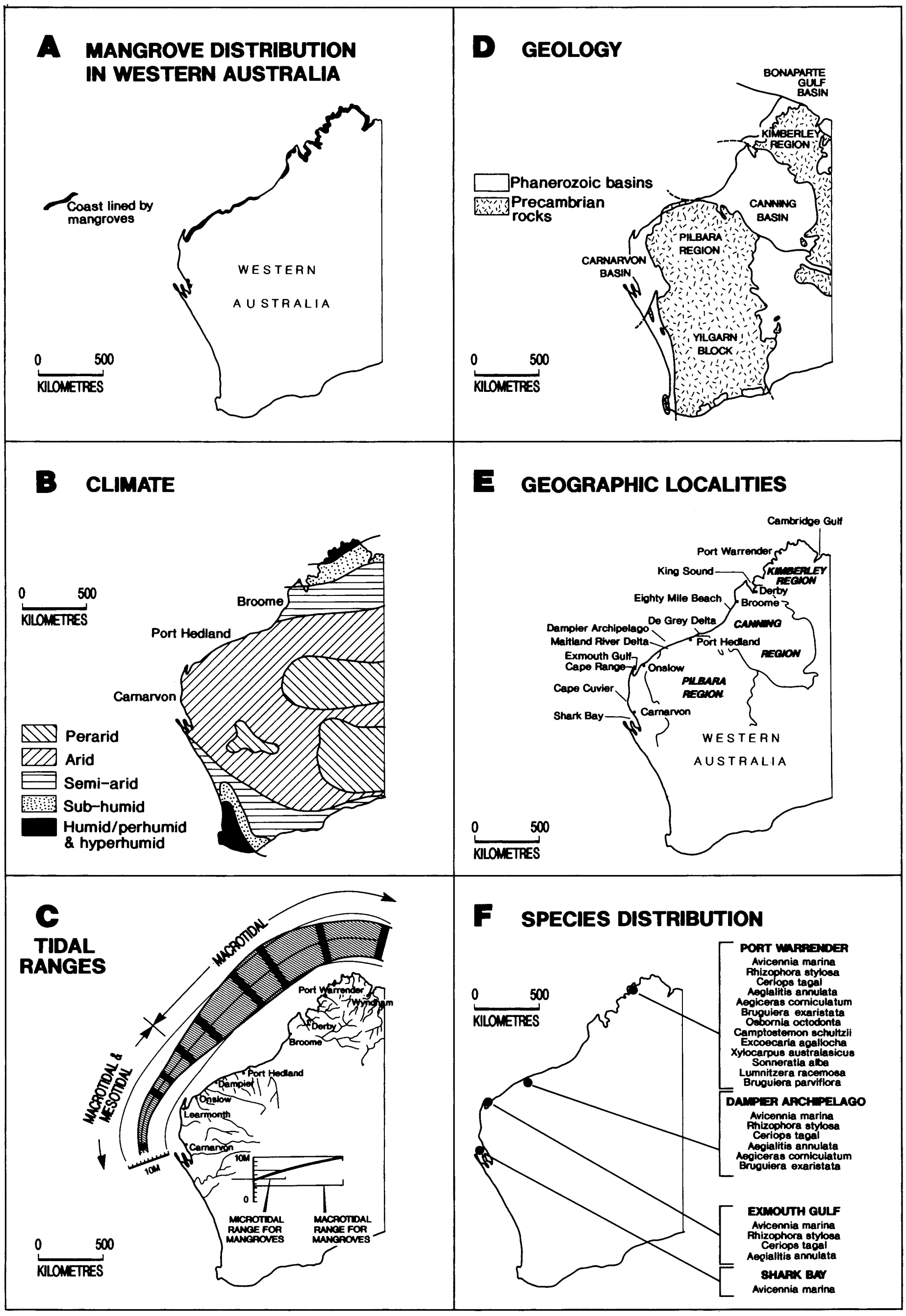


Figure 2. Mangroves in Western Australia (after SEMENIUK, 1993b): background factors. (2A) Distribution of mangroves in Western Australia. (2B) Climate setting (after GENTILLI, 1972). (2C) Tidal regime. (2D) Geological setting (after GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, 1976), showing the variable geological provinces the coast intersects. (2E) Main geographic locations mentioned in text. (2F) Change of species richness from humid northern areas to southern arid areas (from SEMENIUK *et al.*, 1978).

dynamics (erosion versus accretion; wave dominated conditions versus tide-dominated conditions; storm activity). With a few notable exceptions, such as the cliffed rocky coasts along the tectonically uplifted Cape Range and Cape Cuvier peninsulas and high energy coastlines such as Eighty Mile Beach (Figure 2E), the mangroves form a nearly continuous fringe along the coast of Western Australia when viewed at the subcontinental scale.

A brief description of the mangrove systems of Western Australia is presented below in terms of: (1) mangrove biogeography, (2) structure and physiognomy, (3) zonation, (4) population maintenance, (5) general edaphic setting, (6) mangrove habitats, and (7) coastal sectors for mangrove systems along the coast of Western Australia. An attempt will be made to show the variability of the systems floristically, ecologically and edaphically.

Biogeography

A total of 17 mangrove species occurs in Western Australia (SAENGER *et al.*, 1977; SEMENIUK *et al.*, 1978; WELLS, 1981, 1982; SEMENIUK, 1983). These are: *Acanthus ebracteatus* Vahl, *Aegialitis annulata* R. Br., *Aegiceras corniculatum* (L.) Blanco, *Avicennia eucalytifolia* Zipp. ex. Miq., *Avicennia marina* (Forsk.) Vierh., *Bruguiera exaristata* Ding Hou, *Bruguiera parviflora* (Roxb.) Wight and Arn. ex Griff., *Camptostemon schultzii* Mast., *Ceriops tagal* (Perr.) C. B. Rob., *Excoecaria agallocha* L., *Lumnitzera racemosa* Willd., *Osbornia octodonta* F. Muell., *Pemphis acidula* J. R. and G. Forst., *Rhizophora stylosa* Griff., *Scyphiphora hydrophylacea* Gaertn., *Sonneratia alba* Sm., *Xylocarpus australasicus* Ridley (probably = *X. mekongensis* Pierre; see discussion in TOMLINSON, 1986). The most common and widespread species are *Avicennia marina, Rhizophora stylosa, Bruguiera exaristata, Ceriops tagal, Aegialitis annulata* and *Aegiceras corniculatum.*

Fifteen species occur in the northern, humid parts of the region. This number progressively decreases towards the southern, more arid parts of the region to four species in Exmouth Gulf and only one species in Shark Bay (Figure 2f).

Structure and Physiognomy

The mangroves in Western Australia are variable in their structure and physiognomy in relationship to climate and to their setting on the tidal flat. Tall forest formations tend to be common in the humid regions and scrub and heaths ("dwarf forests") in the more arid regions. In terms of physiognomy, the mangrove trees and shrubs vary from being slender-trunked in humid forest settings to recumbent, gnarled, or mallee-form in more arid settings. There is also a structural and physiognomic variation within the mangroves across the tidal flat, following decreasing frequency of inundation of seawater and increasing salinity of groundwater. Forests, low forests and scrub dominate seaward parts of the mangrove belts, whereas scrub and heath dominate landward parts. In humid areas there is gradation from forests in seaward parts of mangrove belts to scrub and heath in landward parts. In arid zones the gradation is from recumbent and gnarled low forests and scrub in seaward parts to mallee-form heath and "dwarf forests" in landward parts of the mangrove belts.

Zonation

Mangroves also exhibit compositional zonation across the tidal zones. This zonation depends on the type of physico-chemical gradient within the tidal zone (*e.g.*, salinity, inundation frequency, or substrate grainsize), type of habitat, and species pool. Variation of zonation of mangroves across the climatic regions of Western Australia and between habitat types across the different climatic regions of northern and northwestern Australia are documented in SEMENIUK *et al.* (1978) and SEMENIUK (1983, 1985).

In the species-rich tropical humid areas there is marked zonation of mangroves. For instance, on a muddy tidal flat, there is:

- a seaward zone of *Sonneratia alba,*
- a zone of *Avicennia marina,*
- a zone of *Camptostemon schultzii,*
- then *Rhizophora stylosa,*
- a mixed landward zone of *Avicennia marina, Aegialitis annulata, Bruguiera exaristata* and locally pure stands of *Ceriops tagal.*

In arid zones, muddy tidal flats present a more simple sequence:

- a seaward zone of *Avicennia marina,*
- a middle zone of *Rhizophora stylosa,*
- landward zone of *Avicennia marina,* with local pure stands of *Ceriops tagal.*

Population Maintenance

Population maintenance strategies for the mangroves also vary according to climate and habitat setting. Broadly, two types of maintenance strategies are recognised: seedling production and vegetative reproduction (SEMENIUK, *in preparation*). Where mangrove systems are maintained by seedlings, the population structures reflect stages from seedling to adult forms. With vegetative reproduction, the mangrove populations are maintained by vegetative extension processes: *i.e.*, new detached plants are produced by root growth from branches and subsequently isolated from the "parent" to form individual and detached "daughter" plants; longevity of individual "parent' trees and shrubs is also maintained by the continual production of basal limbs and subsidiary trunks through epicormic shoot production. Where vegetative propagation is dominant, the population structures and vegetation structure/physiognomy exhibit an adult-dominant composition of mature and over-mature individual forms. Vegetative propagation may occur in humid and arid climates, but seems to be more of a feature of arid settings where salinity of soils is elevated sufficiently to be toxic to seedlings.

The common species in Western Australia, *Ceriops tagal, Bruguiera exaristata, Aegialitis annulata* and *Aegiceras corniculatum* maintain their populations by seedlings in all settings and all climatic regions. *Avicennia marina* and *Rhizophora stylosa* exhibit variation in maintaining their populations according to habitat and to climate setting. They maintain their populations by both seedling production and vegetative propagation in humid settings and in local habitats (such as sandy tidal flats or margins of spits) in arid climates. However, they predominantly utilise vegetative propagation to maintain their populations in most habitats in arid climates. As a general pattern, for *Avicennia marina* and *Rhizophora stylosa,* mangrove populations in humid climates are maintained by seedling production. In arid climates, there is a tendency for vegetative propagation.

General Edaphic Setting

Since mangroves occupy the mid to upper tidal zone, edaphic processes and products within this zone determine the occurrence and survivorship of their populations. However, geomorphic, sedimentologic and hydrologic processes below and above the mid-upper tidal zone also influence the mangrove habitat. For example, sedimentological processes distal to the immediate zone of mangroves may prepare the landform and substrates for mangroves and develop the larger scale stratigraphic framework for the interactions of recharge and discharge of groundwater. The essential edaphic components of the mangrove systems in Western Australia are the geomorphic setting, the substrate types, sedimentologic processes, the stratigraphic sequence, and the groundwater/soilwater complex (SEMENIUK, 1983, 1985, 1986, 1993b; SEMENIUK and WURM, 1987).

The Quaternary stratigraphy of mangrove areas is important for at least two reasons. First, it provides a historical context for the origin and distribution of substrates and consequently for habitats. Thus, it provides information on the longevity and maintenance of mangrove-vegetated habitats since the sedimentary (biotic) lithotopes can form distinctive stratigraphic units. Second, the stratigraphy forms the basic framework for the tidal zone hydrology and for the tidal zone/hinterland hydrologic exchanges. Since groundwater salinity, recharge, and mixing are important physico-chemical elements of mangrove ecosystems, it follows that the stratigraphic array of aquifers and aquatards is an important component of these systems.

Generally three types of sedimentologic systems are developed in the tidal zone and produce a stratigraphic sequence that either fills the main part of any embayment or underlies open coastal tidal flats: (1) tidal flats wholly underlain by sand resulting in a stratigraphic profile of sand; (2) tidal flats underlain by sand in low- to mid-tidal zones, and by mud in mid to upper tidal zones, resulting in a stratigraphic sequence of mud underlain by sand; and (3) tidal flats wholly underlain by mud resulting in a stratigraphic profile of mud (SEMENIUK, 1993a; SEMENIUK and WURM, 1987). Mud in these systems may be terrigenous or carbonate (SEMENIUK, 1993b); mangrove peat is not a common type of sediment in these systems. These three types of gross stratigraphic sequences are complicated by local incursive units of alluvial fans, spits/cheniers, or hinterland-fringing sediment aprons. These form stratigraphic units interfingering along the margin of the main tidal flat sedimentary wedge or occurring as units embedded within the wedge (SEMENIUK, 1980b, 1983, 1985; SEMENIUK and WURM, 1987). All these stratigraphic units and their variable permeabilities and porosities form the framework to the tidal flat groundwater system. They function as discrete aquifer reservoirs or conduits through which groundwater is preferentially recharged or discharged.

The occurrence, depth, and salinity of the groundwater/soilwater systems on tidal flats and adjoining hinterland are important hydrologic factors that regulate mangrove populations or influence mangrove zonation (MACNAE, 1968; CHAPMAN, 1976; CINTRON *et al.*, 1978; SEMENIUK, 1983, 1985). Groundwater/soilwater can be classified on geomorphic/habitat and stratigraphic occurrence and on salinity. The salinity of the various groundwater/soilwater units can be shown to be closely linked to stratigraphy, substrate, recharge mechanisms and evapo-transpiration. There are six main bodies of groundwater (SEMENIUK, 1985; SEMENIUK and WURM, 1987). These are: (1) hinterland and dune groundwater (freshwater); (2) hinterland and dune margin groundwater (saline/mixed); (3) alluvial fan groundwater (saline/mixed); (4) tidal flat groundwater (saline); (5) spit/chenier groundwater (saline/mixed); (6) rocky shore groundwater (saline). Within each of these there is a gradient of salinity. For example, for tidal flats, this ranges from seawater to over 200,000 ppm in a gradient from MSL to landward on tidal flats; for units along the hinterland margin or that receive fresh water, this ranges from freshwater to hypersaline in gradients from landward to seaward. Evaporation on the higher tidal parts of the tidal flat results in development of hypersaline flats or salt flats devoid of mangroves in arid, semi-arid and subhumid climates.

Mangrove Habitats and Mangrove Assemblages in Western Australia

The combination of geomorphology, substrates, stratigraphy, aquifers and salinity at small scales develops the various habitats for the mangroves. The main mangrove habitats in Western Australia are diagramatically illustrated in Figure 3. Some of these habitats are long-term stable, while others are dynamic.

These habitats are the fundamental units that support the various mangrove assemblages. For a given climatic region, they will tend to support a distinct floristic assemblage, or at least a distinctive assemblage identified on both floristics and vegetation structure/physiognomy. For example, a limestone pavement situated between MSL and HWN (MSL = mean sea level, HWN = high water neap tide) will support a different floristic and structural/physiognomic assemblage to that of a muddy tidal flat or that of a sandy tidal flat between the same tidal levels. A comparison between similar habitats in different climatic settings will show that they support different floristic assemblages across the climate zones because the mangroves are drawn from differing species pools (SEMENIUK, 1985).

This facet of habitat types and their related mangrove associations (with distinct floristic assemblages or structural/physiognomic types) is the baseline for predicting some of the effects of a sea-level rise into heterogeneous coastal systems. Within a given climatic region today, the various habitats in a coastal sector support associations of mangroves whose composition, structure or physiognomy are related to a specific habitat setting (Figure 4).

For instance, under conditions of the current sea level position, within a coastal sector in microtidal regime, there may be three types of coastal landforms with or without mangroves: a MSL-HWN limestone pavement supporting simple *Avicennia marina* scrub, a muddy tidal flat supporting zoned mangroves (from seaward to landward: *Avicennia marina* forest, *Rhizophora stylosa* scrub, and *Avicennia marina* scrub), and a salt flat devoid of mangroves, underlain by limestone pavement. Sea level rising into this system will more frequently inundate the salt flat so that it will become a MSL-HWN limestone pavement habitat. The current association of simple *Avicennia marina* scrub inhabiting a limestone pavement would indicate that a similar assemblage should inhabit the newly formed MSL-HWN limestone pavement.

Within each habitat type illustrated in Figure 3, there are physico-chemical gradients in: (1) frequency of inundation, (2) substrate sediment texture, (3) chemistry and mineralogy of the soils, (4) soil moisture, and (5) salinity of groundwater/soilwater. These gradients result in zonation of mangroves (*cf.* SEMENIUK, 1985; SEMENIUK and WURM, 1987).

Mangrove vegetation in Western Australia is difficult to classify at the large to regional scale because there exists much compositional and structural variation. Even at the local scale there commonly is heterogeneity because of small scale changes and physico-chemical gradients within habitats. Mangrove systems overseas, composed

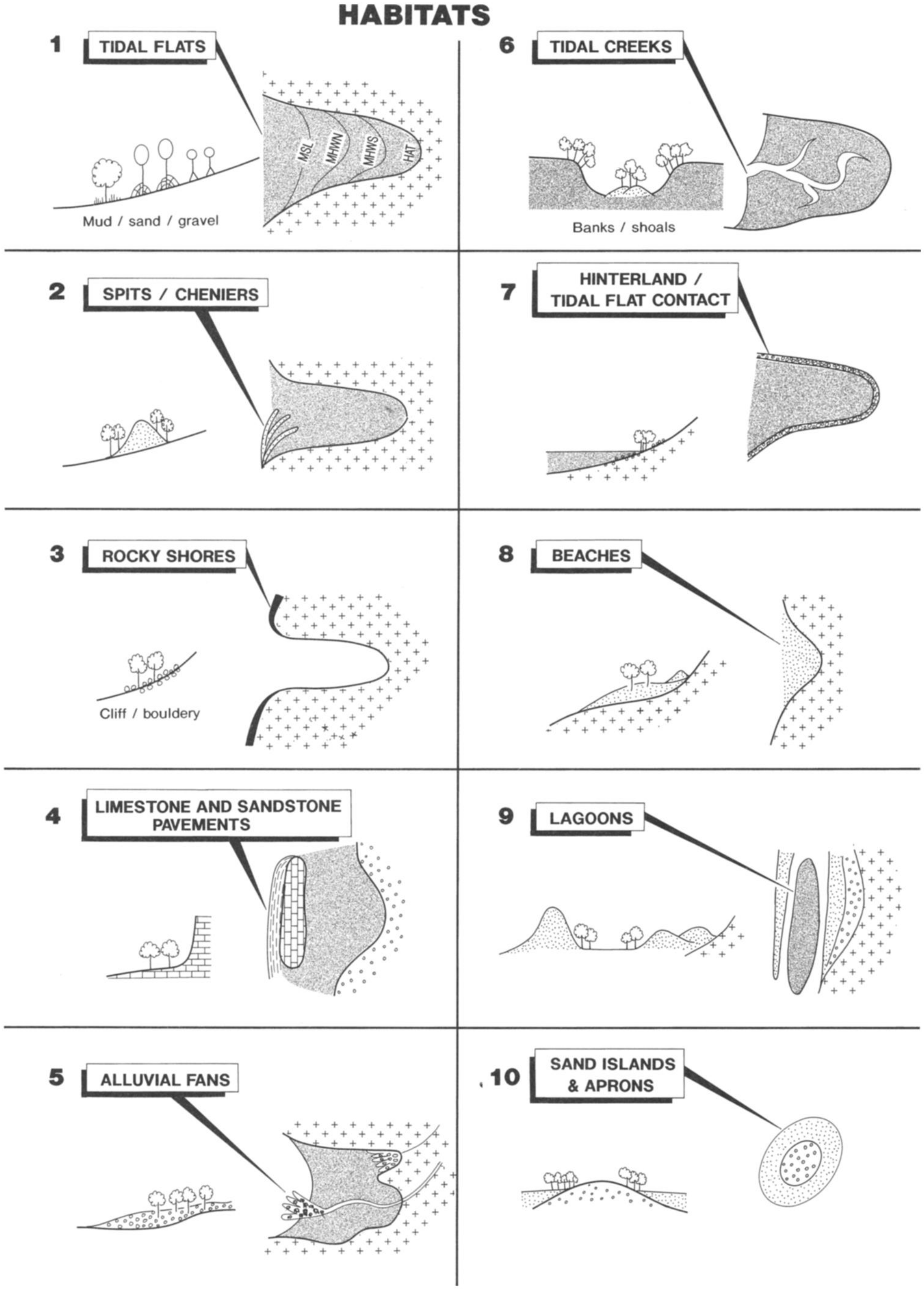
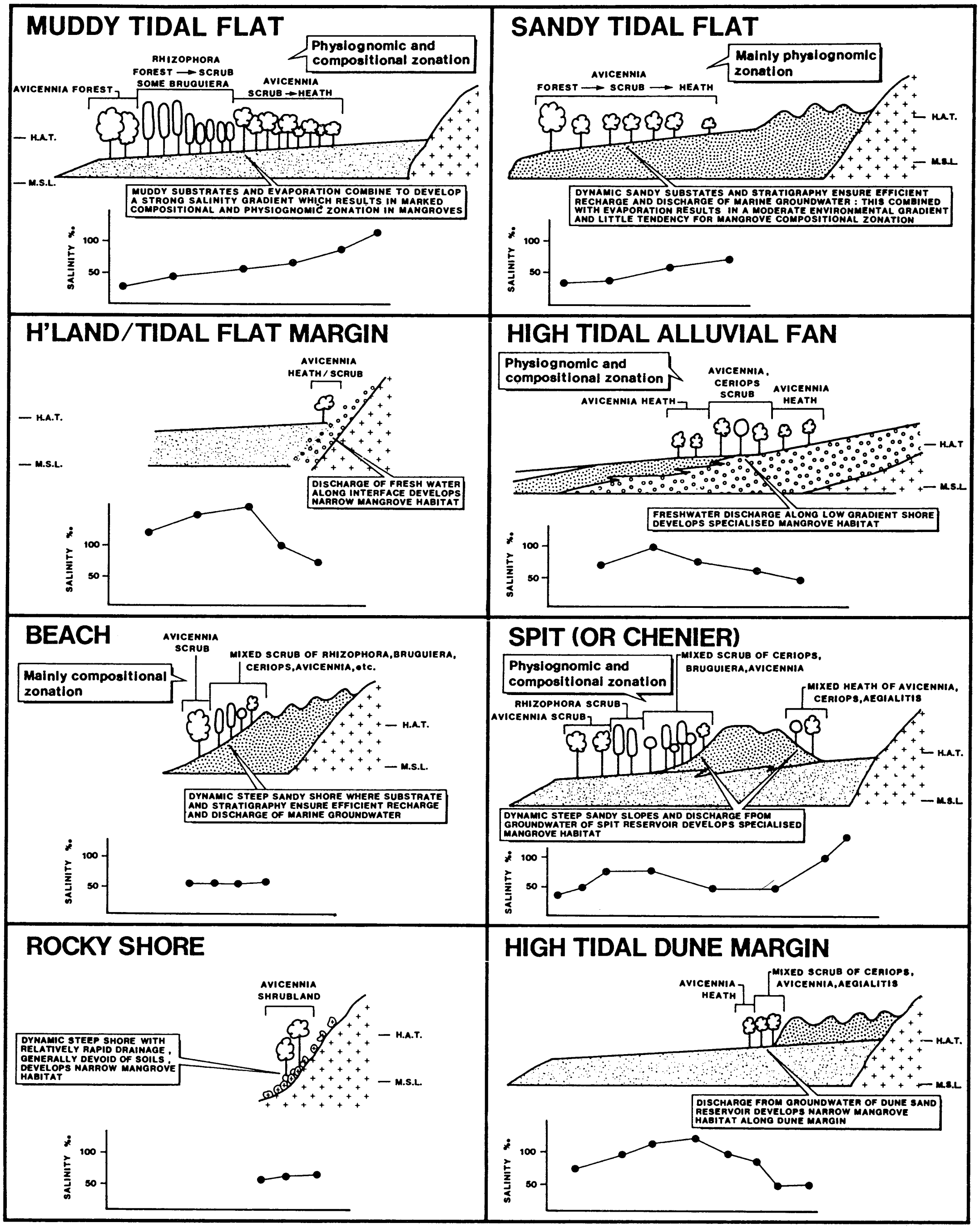


Figure 3. Main habitats for mangroves in Western Australia (after SEMENIUK, 1993b). Each type is illustrated by a plan view and a cross section, with the location of the mangrove formation within the habitat shown.



MUDDY SUBSTRATES AND EVAPORATION COMBINE TO DEVELOP A STRONG SALINITY GRADIENT WHICH RESULTS IN MARKED COMPOSITIONAL AND PHYSIOGNOMIC ZONATION IN MANGROVES

DYNAMIC SANDY SUBSTATES AND STRATIGRAPHY ENSURE EFFICIENT RECHARGE AND DISCHARGE OF MARINE GROUNDWATER : THIS COMBINED WITH EVAPORATION RESULTS IN A MODERATE ENVIRONMENTAL GRADIENT AND LITTLE TENDENCY FOR MANGROVE COMPOSITIONAL ZONATION

DISCHARGE OF FRESH WATER ALONG INTERFACE DEVELOPS NARROW MANGROVE HABITAT

FRESHWATER DISCHARGE ALONG LOW GRADIENT SHORE DEVELOPS SPECIALISED MANGROVE HABITAT

DYNAMIC STEEP SANDY SHORE WHERE SUBSTRATE AND STRATIGRAPHY ENSURE EFFICIENT RECHARGE AND DISCHARGE OF MARINE GROUNDWATER

DYNAMIC STEEP SANDY SLOPES AND DISCHARGE FROM GROUNDWATER OF SPIT RESERVOIR DEVELOPS SPECIALISED MANGROVE HABITAT

DYNAMIC STEEP SHORE WITH RELATIVELY RAPID DRAINAGE, GENERALLY DEVOID OF SOILS, DEVELOPS NARROW MANGROVE HABITAT

DISCHARGE FROM GROUNDWATER OF DUNE SAND RESERVOIR DEVELOPS NARROW MANGROVE HABITAT ALONG DUNE MARGIN

Figure 4. Summary diagram showing key habitat features such as slope, salinity gradients, substrates, and physico-chemical processes, and the resulting mangrove composition, structure and physiognomy in a ria coastal setting in the Dampier Archipelago (after SEMENIUK and WURM, 1987).

of fewer floristic components, have been classified into structural types (*e.g.*, the riverine basin, fringing and dwarf categories of LUGO and SNEDAKER (1974). This approach has not been successfully used in Western Australia. The structural schemes of SPECHT (1981), or floristic schemes of CHAPMAN (1976), used in isolation, also are not successful because the complex floristics and structure, respectively, are not involved in the nomenclature.

In Western Australia, mangrove vegetation has been classified, at a primary level, according to habitat (SEMENIUK, 1985; SEMENIUK and WURM, 1987). This assumes that as there are physiochemical variations in the habitat, variations in structural and floristic gradation and zonation of mangroves will occur within the assemblages. The main mangrove assemblages recognised are: (1) muddy tidal flat assemblages; (2) sandy tidal flat assemblages; (3) gravelly tidal flat assemblages; (4) spit/chenier assemblages; (5) rocky shore assemblages; (6) limestone pavement assemblages; (7) sandstone pavement assemblages; (8) alluvial fan assemblages; (9) tidal creek assemblages; (10) hinterland fringe assemblages; (11) beach assemblages; (12) lagoon assemblages; and (13) sand islands and apron assemblages. Some of these types are specific to certain geomorphic settings, whereas others occur throughout tropical Western Australia. In addition to variation in habitats locally and regionally, there is compositional (floristic) variation regionally in response to climate. Thus, the floristic assemblages that colonise similar habitats will vary from region to region. Mangrove belts and zones within a habitat may be further classified by structure and floristics at a secondary level (SEMENIUK and WURM, 1987).

Coastal Sectors for Mangrove Systems in Western Australia

There are seven coastal sectors for mangroves in tropical Western Australia (SEMENIUK, 1993b). Four main features determine location and nature of these sectors (Figures 2b, and c and 5): (1) the style and amount of fluvial input from the hinterland to the coastal zone, (2) the mineralogical nature of mud in the mangrove environment, (3) the climatic setting of the coast, and (4) the nature of the oceanographic regime that receives the sediment. From north to south, these sectors are (Figures 5a and 6):

(1) Cambridge Gulf,
(2) Kimberley Coast,
(3) King Sound,
(4) Canning Coast,
(5) Pilbara Coast,
(6) Rowley Shelf Province,
(7) Carnarvon Province.

Each of the coastal sectors has a distinct range of large-scale coastal landforms, producing local geomorphic and sedimentary patterns (Figure 6) and a profusion of smaller scale habitats. Many distinctive and unique mangrove populations have developed in these smaller scale habitats. A description of these sectors and a summary of the mangrove habitats within them, drawn from SEMENIUK (1993b) follows.

Cambridge Gulf, in a semi-arid climate, has mangrove habitats in a tide-dominated, macrotidal estuarine-gulf environment. The hinterland is uplifted Precambrian rocks flanked by aprons of alluvium (THOM *et al.*, 1975). The gulf is located along the structural edge of the Kimberley Block, which has been scoured out by large rivers of the region. These rivers deliver terrigenous sediment to the shore. Tidal deposits that partly fill the gulf are sand overlain by mud. Within the gulf mangrove habitats are broad tidal flats, large scale channels, sediment islands, shoals, and spit/chenier systems (THOM *et al.*, 1975).

The Kimberley Coast, in a humid to semi-arid climate, has mangrove habitats in a tide-dominated, macrotidal ria-archipelago setting with the coast fringing the dissected Kimberley Plateau (Precambrian rock). A series of short rivers develop the rias and deliver terrigenous sediment to the shore. Along the coast are the following regional scale coastal types: ria coasts, with narrow embayments, broad embayments, straight coasts and islands; tidal-land connected islands; and archipelagos, whose margins have the same suite of units as ria coasts. Within the large scale embayments, there are mangrove habitats of tidal flats, tidal creeks, spits, alluvial fans, rocky shores and hinterland margins (SEMENIUK 1985).

King Sound comprising the Fitzroy River estuary and Stokes Bay has a semi-arid climate. It also has mangrove habitats in a tide-dominated, macrotidal estuarine-gulf environment (JENNINGS and BIRD, 1967; JENNINGS, 1975; SEMENIUK, 1981a), similar to Cambridge Gulf. The gulf is a marine-flooded former large valley scoured out by large rivers that have selectively eroded the structural junction between Precambrian and Meso-

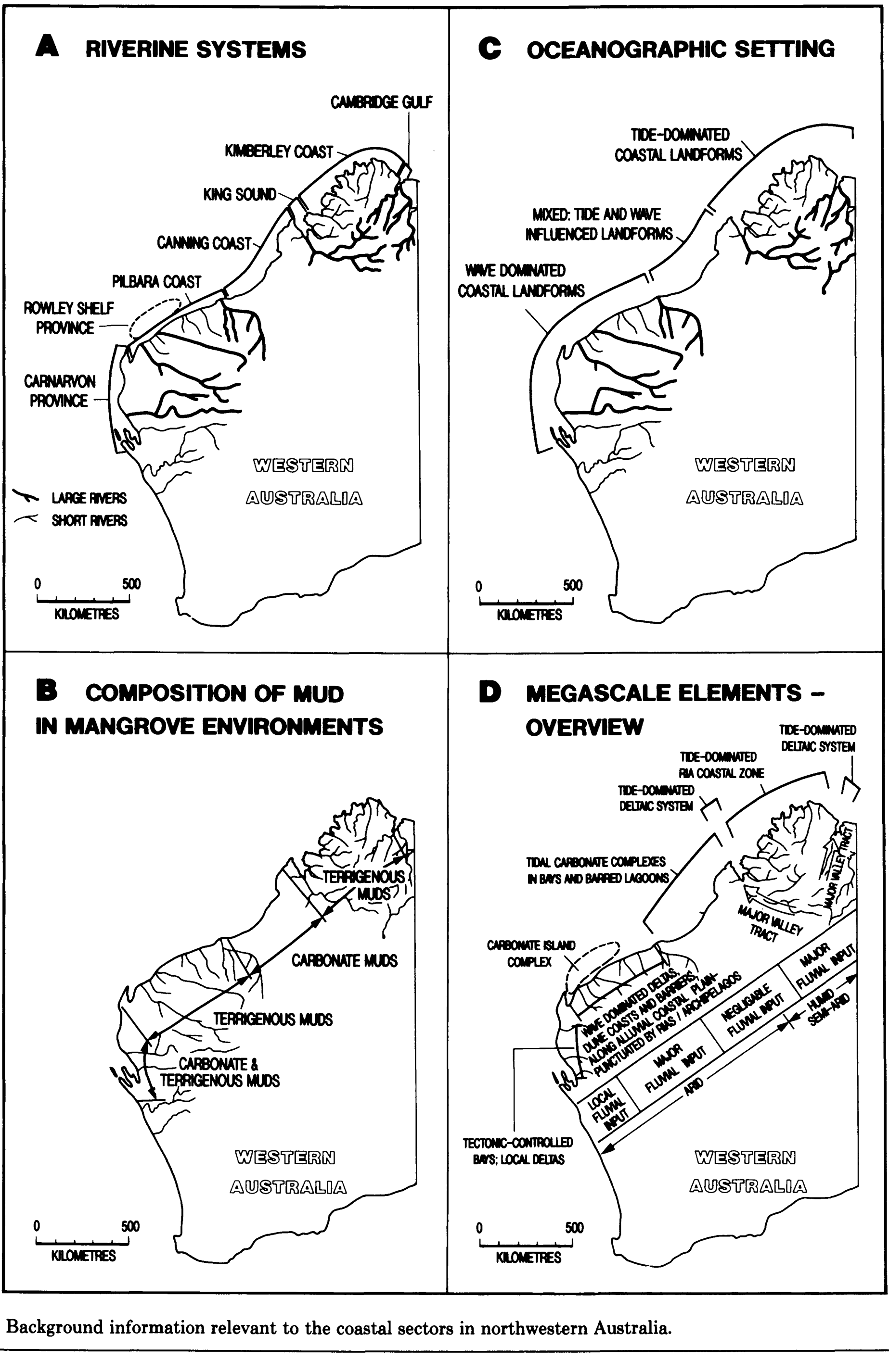


Figure 5. Background information relevant to the coastal sectors in northwestern Australia.

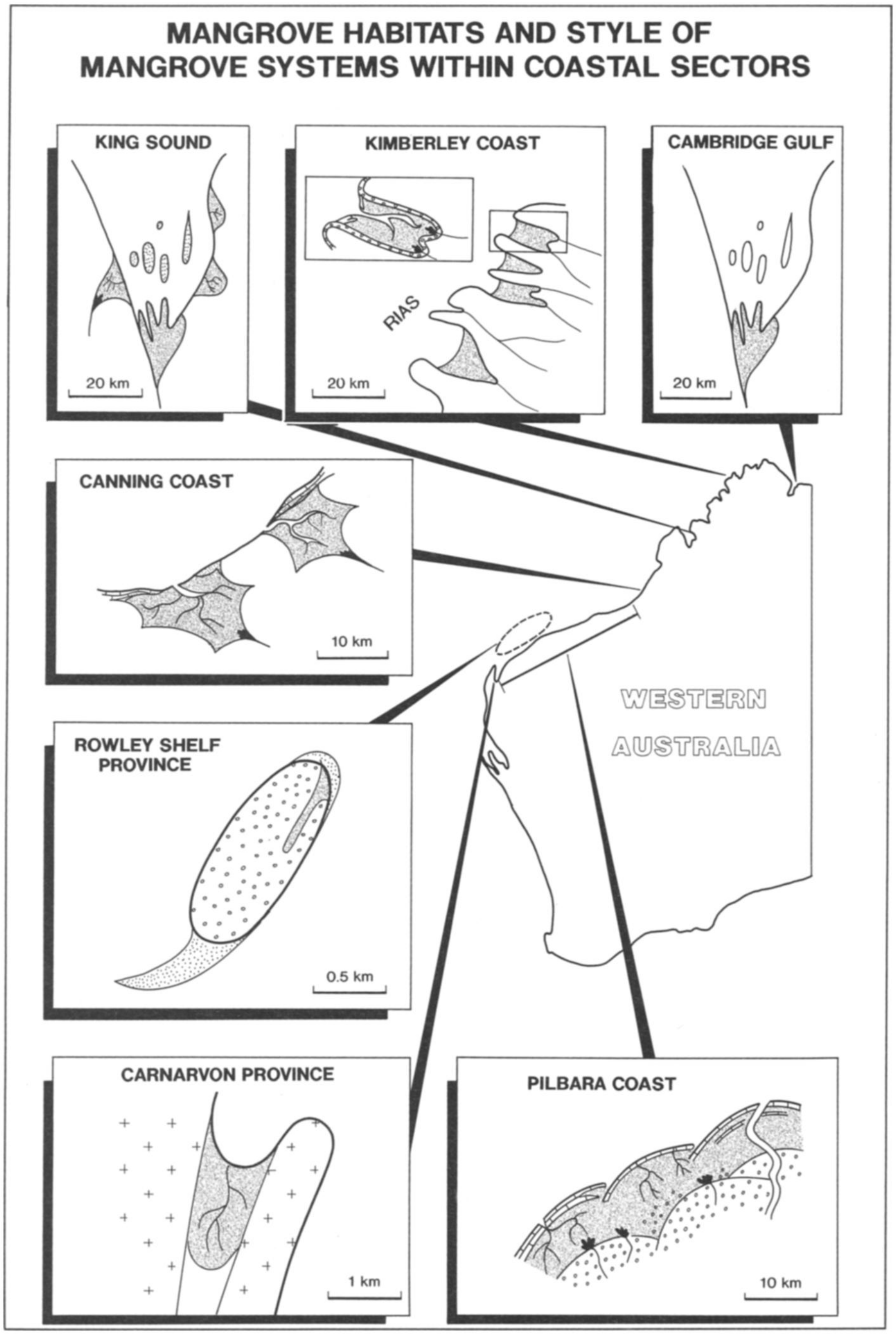


Figure 6. Summary of mangrove habitats and style of mangrove systems within the coastal sectors (after SEMENIUK, 1993b).

zoic rocks. The hinterland is of Mesozoic rock overlain by Quaternary linear dunes. Large rivers deliver terrigenous sediment to the gulf, and Holocene tidal deposits that partly fill the gulf are sand overlain by mud (SEMENIUK, 1980b). These truncate and overlie the linear dune system (JENNINGS, 1975). Most of the tidal land in this area is eroding on a large scale, and the various coastal features there are products of this process (SEMENIUK, 1980a, 1981a). The tidal zones have been classed by geomorphology into seven types (SEMENIUK, 1981a, 1993b): (1) depositional flats, (2) unconformity flats, (3) shoal flats, (4) spit/chenier flats, (5) rocky shores, (6) mid-gulf shoals and (7) islands. These seven units also form the basis of the main mangrove habitats in this sector.

The Canning Coast, in a semi-arid to arid climate, has mangrove habitats in a barred to open macrotidal embayments in a coastal regime that is both wave- and tide-influenced. The Canning Coast is the shore cut into the Canning Basin and forms the seaward edge of the Great Sandy Desert. There are no major river outlets. With little or no fluvial run-off from a predominantly desert dune hinterland, terrigenous mud is negligible; carbonate mud is dominant in mangrove environments. Pre-Holocene erosion of Mesozoic rock and Cainozoic aeolian hinterland has formed shallow valleys. These have developed into a series of scalloped embayments now partly filled with mud and vegetated by mangroves. Locally, barrier spits and dunes have formed at the headlands of the embayments.

The Pilbara Coast, in an arid climate, ranging from microtidal in the south to macrotidal in the north, has mangrove habitats in wave-dominated settings of deltas, beach/dune coasts, limestone barrier islands, and ria-archipelago shores. Within these there is a multitude of varied large, medium and small-scale coastal landforms. Sedimentary deposits such as spits, sand mounds and shoals, sand aprons around islands, alluvial fans, tidal creeks, etc., often specific to a particular coastal setting, form habitats for mangroves. The Pilbara Coast is the most complex of mangrove coasts in northwestern Australia. The unifying feature of this coast is that it is a sedimentary repository for a range of rivers that drain a high relief Precambrian rocky hinterland and deliver terrigenous sediment to the shore. The rivers discharge sediments along a coastal plain which fronts a wave-dominated environment in an arid climate. The combination of fluvial and shoreline accretion processes, coastal cementation, coastal erosion, and ancestral landform architecture, such as residual Pleistocene limestone ridges and large outcrops of Precambrian bedrock, has produced a laterally heterogeneous coastal system (SEMENIUK, 1993a). Prevailing winds develop coastal dunes, and influence the construction of coastal sediment bodies by wind waves (SEMENIUK and WURM, 1987). Cyclones (hurricanes) are common (COLEMAN, 1971; MILTON, 1978; LOURENZ, 1981). They cause flash flooding, marked river discharge of sediment into the coastal plain, accumulation of spits in the coastal zone, and erosion and dispersion of coastal sediment bodies. Long-period swell, local wind waves, landbreeze/seabreeze systems and thunderstorms contribute to develop wave-dominated coastal landforms such as deltas, beaches, spits and bouldery shores (STEEDMAN, 1985; STEEDMAN and COLMAN, 1985; SEMENIUK, 1985; SEMENIUK and WURM, 1987).

The Rowley Shelf Province, in an arid, oceanic setting, comprises small oceanic islands on the Northwest Shelf of Western Australia. Mangrove habitats occur in small embayments along the wave-dominated island shores and in lagoons of the island interiors. The Carnarvon Province, in an arid climate, is part of the modern Carnarvon Basin (GEOLOGICAL SURVEY OF W.A., 1976; LOGAN *et al.*, 1970). It exhibits considerable heterogeneity because of its strong tectonic history in the Cenozoic. North-trending uplifted anticlinal structures, composed of Tertiary sedimentary rocks, locally form peninsulas, barriers and ridges. These cradle small to large, protected to sheltered, embayments in which the mangrove environments are developed (BROWN 1976). Tectonic uplift has diverted a number of rivers and only two reach the sea to form the Gascoyne delta (JOHNSON 1982) and the Wooramel delta. These deliver terrigenous sediment to the shore; locally, there is carbonate in the mangrove environment. Mangroves in this sector inhabit the bays (synclines) that intersect the coast, the barred lakes, and the wave-dominated deltas; they colonise tidal flats, margins of spits, borders of lagoons, and the strandplains and tidal creeks within deltas.

ENVIRONMENTAL FACTORS THAT WILL AFFECT THE RESPONSE OF MANGROVES TO SEA-LEVEL RISE

In Western Australia some of the key factors that determine the occurrence of mangroves along the coast are: (1) the geomorphic setting of the mangrove system, (2) the sedimentologic processes along the coast, (3) the salinity structure of the groundwater/soilwater system, and (4) the maintenance strategies utilised by the mangrove populations. Other factors such as nutrient dynamics, fauna activity (SEMENIUK and WURM, 1987) and microclimate also have some influence, but are not considered here.

The geomorphic setting of mangrove systems comprises a range of inter-related factors such as substrate types, coastal processes, sediment delivery, and freshwater delivery, all of which influence the occurrence and survivorship of mangroves. The sedimentological processes, involving physical, biological and chemical processes of sedimentation, determine at the local scale the structural, textural and mineralogical properties of the substrates, sediment mobility, stratigraphic sequence, and chemical products (*e.g.*, cemented pavements and beach rock). At a larger scale, these processes determine the stability or mobility of sediment bodies such as spits, cheniers and dunes. The salinity structure refers to the array of aquifers and to the three-dimensional configuration of groundwater and soilwater salinity. Population maintenance strategies refers to how mangrove vegetation maintains viable populations within their habitat.

The approach used in this paper to predict the potential effects of a sea-level rise on mangroves is to first describe the variable geomorphologic, sedimentologic, and hydrologic settings along the mangrove coasts in Western Australia and the population dynamics of mangroves systems in the various climatic and habitat settings. This forms the theoretical basis to predicting the potential effects of a rising sea level on varied mangrove systems. These potential effects are discussed below in terms of environmental setting of mangroves in Western Australia, sedimentological adjustments, and the stratigraphic sequences developed in relation to the late Holocene interval.

Influence of Environmental Setting on Mangrove Responses to Sea-Level Rise

The essential environmental factors that will influence the variable response of mangroves to a rising sea level in Western Australia are as follows (Figure 7):

(1) Coastal geomorphology and habitat heterogeneity will determine: first, whether there will be a uniform or heterogeneous sedimentologic response at the small scale, and second, whether mangroves will encroach onto a mosaic of substrate types or a relatively uniform substrate.

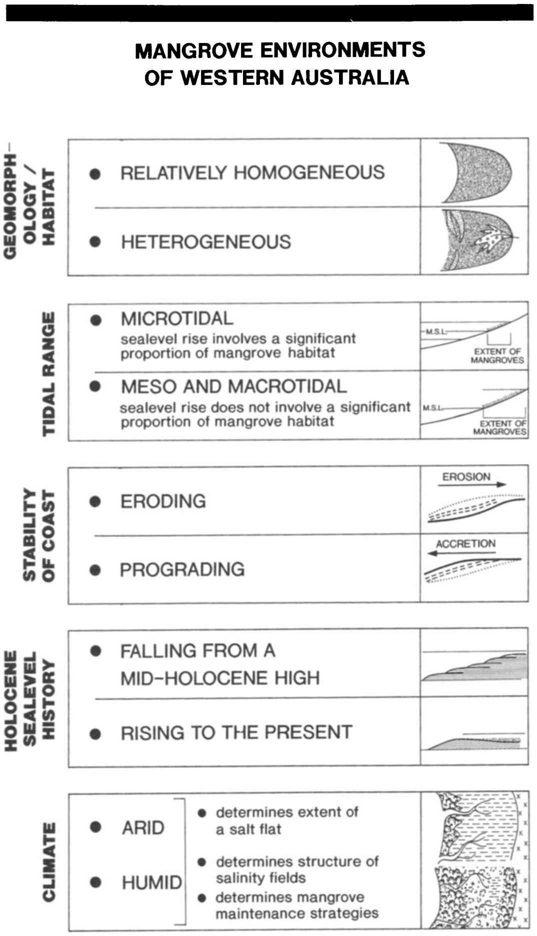


Figure 7. Environmental factors that will influence the variable response of mangroves to a rising sea level.

(2) Tidal range will determine whether or not a sea-level rise will involve a significant proportion of the present mangrove habitat. For areas around Shark Bay and Exmouth Gulf, that are microtidal, a predicted rise of 50 cm will completely inundate the existing mangrove zone. It, thus, must result in a wholesale shift and re-establishment landward of the mangrove zone. For areas that are macrotidal, the predicted rise in sea level may be only 5–10% of the total tidal range and will not have the same effect.

(3) Whether the coast is eroding or accreting will determine whether a sea-level rise will encroach into an eroding coastal system and potentially exacerbate the situation, or into an accreting coast and potentially change the sedimentary budget of the system (*e.g.*, by reworking sedimentary material currently stored out of reach of wave base).
(4) The origin of the upper tidal flat (*i.e.*, due to a falling or rising Holocene sea level history) into which potential mangrove encroachment will occur determines whether the rising sea will encroach onto a shore with a small or large gradient. A very small rise in sea level onto a coast with a very low to negligible gradient will result in significant lateral incursion and flooding. A similar rise onto a coast that has a steeper gradient will involve a less dramatic incursion.
(5) Whether the system occurs in an arid or humid climate will determine the structure of the salinity fields under the tidal flats, the extent of the salt flat landward of the mangroves, and the dominant type of mangrove population maintenance.

SEDIMENTOLOGICAL ADJUSTMENTS

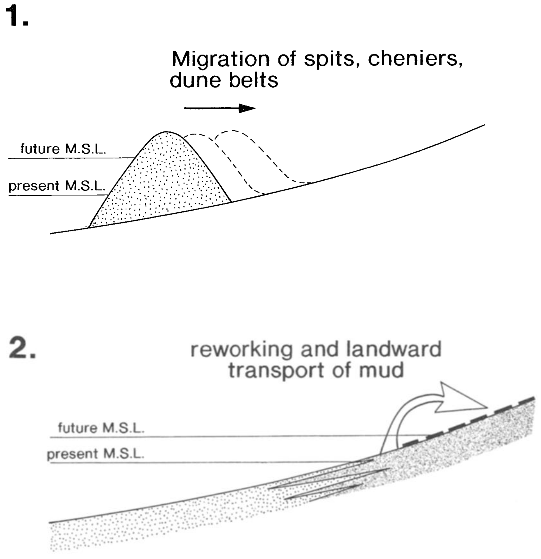


Figure 8. Types of sedimentologic adjustments to a rising sea level.

Sedimentological Adjustments in Response to Sea-Level Rise

An important component of the mangrove environment is the sedimentologic system. Where mangroves inhabit accreting or eroding sedimentary systems (rather than stable substrates such as rock pavements), the survivorship of mangroves is linked to the sediment dynamics. In general, the sedimentary facies of a tidal flat are in equilibrium with the prevailing mean sea level and position of average (long term) wave base. Short term adjustments, in the location and intensity of sedimentological processes and in the disposition of lithotopes and microfacies, occur as storms, and aperiodic weather effects take place. This results in the migration of facies boundaries to a small extent up and down the tidal zone slope.

The two most important facies relationships in the tidal zone, with respect to a rising sea level, are: (1) sand spits, cheniers and dune belts and their respective relationships to MSL and coastal setting, and (2) the sand to mud transition on the tidal flat slope (Figure 8). In the former, sand bodies emanating from headlands located at erosional cliffs or down-drift from a sand supply, are related to modern prevailing coastal processes and to the current position of MSL. A shift in MSL can potentially cause dis-equilibrium and adjustments of these sand bodies to the new prevailing position of MSL. Where these sand bodies are habitats for mangroves or where they protect habitats for mangroves, readjustments of the position of the sand bodies in relationship to a new MSL position will have effects on the adjoining mangrove belts.

In the latter case, for those tidal flats composed of low tidal sand and upper tidal mud deposits, the tidal height of the sand to mud transition will be determined by the prevailing wave base at high tide, the tidal current regime, and the ratio of sand to mud for that particular coastal setting (Klein, 1985; Masselink and Short, 1993). Whether the sand to mud transition occurs via sand and mud interdigitations, or by a gradation from sand to muddy sand to mud, will depend on the nature of bioturbation and mixing in the transition zone (*cf.* King Sound in Semeniuk, 1981b). For a given site, the location of the sand to mud transition will be a long term average position related to current MSL. A shift in MSL will cause a shift in the position of wave base and hence readjustments of the transition zone by reworking and landward transport of mud.

The Stratigraphic Sequence in Relation to the Late Holocene Interval

Many of the mangrove environments in Western Australia initially developed when the postglacial marine flooding, and coastal progradation took place some 5,000–6,000 years BP. Environments such as high tidal alluvial fans and lagoons formed at this time and are long-term habitats. In addition, other environments have taken thousands of years to evolve through sedimentation, erosion/weathering, or cementation with sea level at its present position. These environments include: high-tidal limestone pavements, cemented beach rock, high-tidal crust pavements, and gravel pavements. Mangroves that colonise these environments are inhabiting systems that have been stable over the millenia. Sea-level rise into such terrains will produce habitats that are in pedogenic, sedimentologic or chemical disequilibrium with the new prevailing MSL position.

To illustrate this principle, consider for instance, the case of hypersaline upper tidal surfaces (salt flats) occurring landward of the mangrove zone. These features illustrate the long-term evolution of surfaces that are in present equilibrium with their hydrologic and chemical environment. With a rising sea level and a sedimentation rate less rapid than the rise, many of the salt flats will be the sites that mangroves normally can be expected to encroach upon as mangrove populations near current MSL are inundated. However, salt flats can be underlain by a range of different materials, such as mud, sand, or limestone. Those underlain by mud may be more amenable to colonisation by mangroves if the increased frequency of inundation decreases their hypersalinity. Other salt flats underlain by sand or sandy mud may have been cemented into crusts at the surface over the past few thousand years (SEMENIUK, 1993a) and are less amenable to colonisation by mangroves, even if the increased frequency of inundation decreases their hypersalinity. Other salt flats cut into Pleistocene limestone by salt weathering from levels above EHWS to levels of tidal influence are not as amenable to mangrove colonisation as soft muddy substrates.

CASE STUDIES OF SELECTED AREAS AS MODELS FOR THE RESPONSE OF MANGROVES TO A SEA-LEVEL RISE

Case studies in Western Australia of natural processes and of responses to industrial impacts simulate a sea-level rise and thus provide useful models for predicting mangrove response to a sea-level rise. Three areas have been chosen:

(1) King Sound,
(2) King Bay in the Dampier Archipelago along the Pilbara coast, and
(3) the Onslow area along the Pilbara coast.

King Sound

King Sound is a macrotidal estuarine-deltaic gulf set in a semi-arid climate (JENNINGS, 1975; SEMENIUK, 1980a) in the King Sound sector. Mangroves line the tidal shores there with up to six mangrove zones parallel to the shore (SEMENIUK, 1980a). The system has extensive salt flats landward of the mangrove vegetation (Figure 9). The tidal shores of King Sound are naturally eroding by sheet, cliff and creek erosion (SEMENIUK, 1980a). They display little variability in terms of habitat and stratigraphy but provide insight into the responses of mangroves to rising sea level.

Sheet erosion, progressing at 1–3 cm/yr, specifically simulates the effects of a rising sea. As the coast retreats, the entire mangrove belt is migrating landwards, generally keeping pace with the retreat. A comparison of aerial photographs taken between 1949 and 1977 shows how, as sheet erosion proceeded, the mangroves encroached into the newly forming habitats (Figure 9). As the tidal flat surface is brought into the range for mangrove habitation, seedlings colonise the new substrates that have become available through the processes of erosion, inundation and dilution of hypersaline groundwater of the salt flats (Figure 9e). Each mangrove zone, as erosion and progressive dilution of hypersalinity proceeds, encroaches landwards, displacing the adjoining one. There is general recruitment towards the landward edge of each zone as each habitat gives way to another over the years. Thus, each mangrove zone is bordered landward by a band of younger plants composed of saplings and seedlings as an understorey to the existing mangrove vegetation. Sea level rising into a system like King Sound would most likely result in the migration of mangroves, with similar composition and structure, into the new habitats formed by increased inundation.

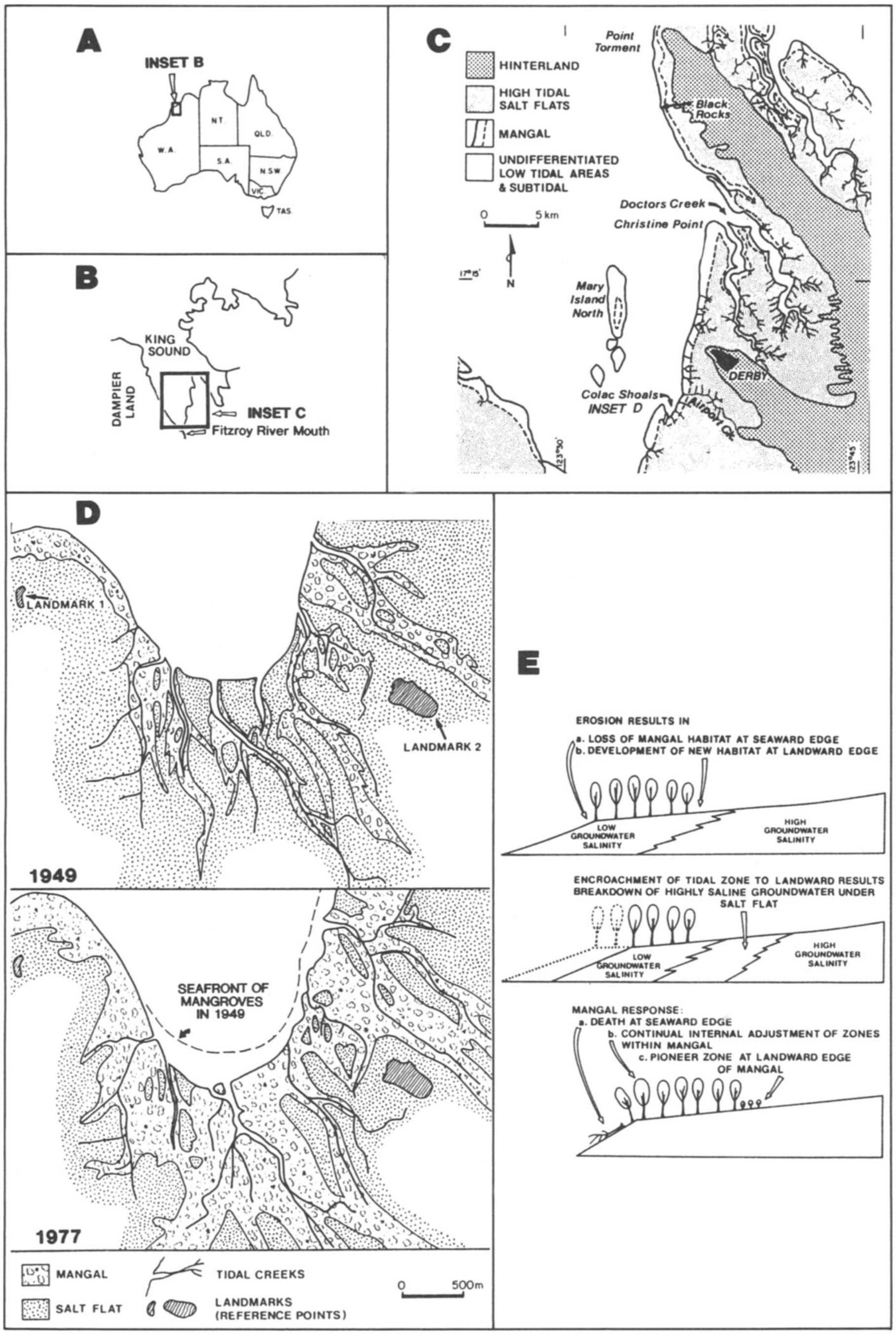


Figure 9. King Sound area. (9A and B) Location. (9C) Mangrove and salt flat distribution. (9D) Comparisons between 1949 and 1977 mangrove distribution: mangroves have encroached landwards (after SEMENIUK, 1980a). (9E) Model of landward encroachment of mangroves in response to sheet erosion (after SEMENIUK, 1980a).

Tidal creek erosion in the King Sound area provides the model for a second type of response. Erosion here involves the slow encroachment of tidal creek headwaters into the upper parts of the salt flat (SEMENIUK, 1981a; KNIGHTON *et al.*, 1992). It is initiated as salt flats erode by sheet erosion (as described earlier) and are brought into more frequent contact with high spring tides. Mangroves then colonise creek banks and slopes as the surface is progressively brought down to the zone of mangrove habitation. The King Sound model would indicate that tidal creek encroachment (erosion) into salt flats would be a part of the general response of muddy tidal flats to a rising sea level.

King Bay

King Bay is a small embayment in the Dampier Archipelago (SEMENIUK and WURM, 1987) in the Pilbara Coast sector. It is a macrotidal system set in an arid climate. Its shores are lined by mangroves, and it is backed by a large salt flat. The mangroves are zoned: a seaward *Avicennia* zone, a middle *Rhizophora* zone, and a landward *Avicennia* zone (Figure 10). The King Bay area furnishes four features that provide some insights for the potential effect of a sea-level rise on mangroves: (1) the stratigraphic sequence that will be out of equilibrium with a rising sea level, (2) the slow erosion of the coastal system, (3) the method of mangrove population maintenance and the encroachment of one zone into another, and (4) the accidental over-run of dredge spoil onto the low tidal flats.

Figure 10 illustrates the stratigraphic sequence under the mangroves in the King Bay area. Each facies currently is in phase with modern sea level. A rise in sea level effectively will place each of these facies out of equilibrium with their formative sea level.

King Bay is slowly eroding by sheet erosion, and it duplicates the situation of a slowly rising sea level, as exemplified by King Sound described above. In King Bay, the tidal flat gradient is 1:100. As a result of the lowering of the tidal flat surface by erosion, there has been a 1.0 m up-slope (horizontal) encroachment of the *Rhizophora* zone into the landward *Avicennia* zone over the past 10 years. This translates into a vertical erosion rate of *c.* 1.0 mm per year. The response of the mangroves to this erosion, is a slow migration upslope, similar to the King Sound pattern.

However, the manner in which mangroves encroach up-slope in King Bay is different to that of King Sound, because of its different population maintenance strategy. Over 15 years of observations within the mangroves of King Bay along transects and fixed quadrats have failed to show evidence of any seedling recruitment to sustain the mangrove populations. Rather, the populations have been maintained by vegetative processes (SEMENIUK, *in preparation*). At the contact between the *Rhizophora* and the landward *Avicennia* zones, there is encroachment of *Rhizophora* shrubs into the *Avicennia* scrub by vegetative extension (Figure 10c). Within the *Rhizophora* zone itself, slow vegetative propagation allows the middle to landward parts to migrate landwards. In contrast, within the *Avicennia* zone, the vegetative growth rates of limbs and branches in the development of new "daughter" plants is too slow to allow continuous migration of this zone landwards. In summary, in arid regions such as King Bay, it appears that *Rhizophora* populations may adjust to an encroaching sea by vegetative extensions but that *Avicennia* may not.

The accidental over-run of dredge spoil onto the tidal flats of King Bay provides a third insight into the response of tidal flats, and hence of mangroves, to a rising sea level. The facies distribution within King Bay consists of sand flats on the low tidal zone, giving way to muddy flats in the mid to upper tidal zone. The transition of sand to muddy sediments is approximately at the level of low water neap tide. In May 1981, there was an accidental over-run of fine-grained dredge spoil (silt and clay) onto the low tidal flats of King Bay (LEPROVOST, SEMENIUK and CHALMER, 1982). This over-run deposited a veneer of mud, 10–100 mm thick, on the sandy tidal flat. This event thus delivered fine material into low tidal environments that are normally winnowed free of mud. Within days, waves began to rework the muddy material, bringing it into suspension; tidal currents transported it landward so that initially a 1–2 mm veener of mud began to coat the surface of the mangrove soils 500 m up-slope. This process of mud winnowing on the lower tidal flats continued for two years until the mud veneer was exhausted.

Similar responses can be expected with a sea-level rise. As the average effective wave base encroaches into muddy environments that normally reside at levels of low water neap tide and higher, muddy substrates will be reworked and transported landward. Sedimentological readjust-

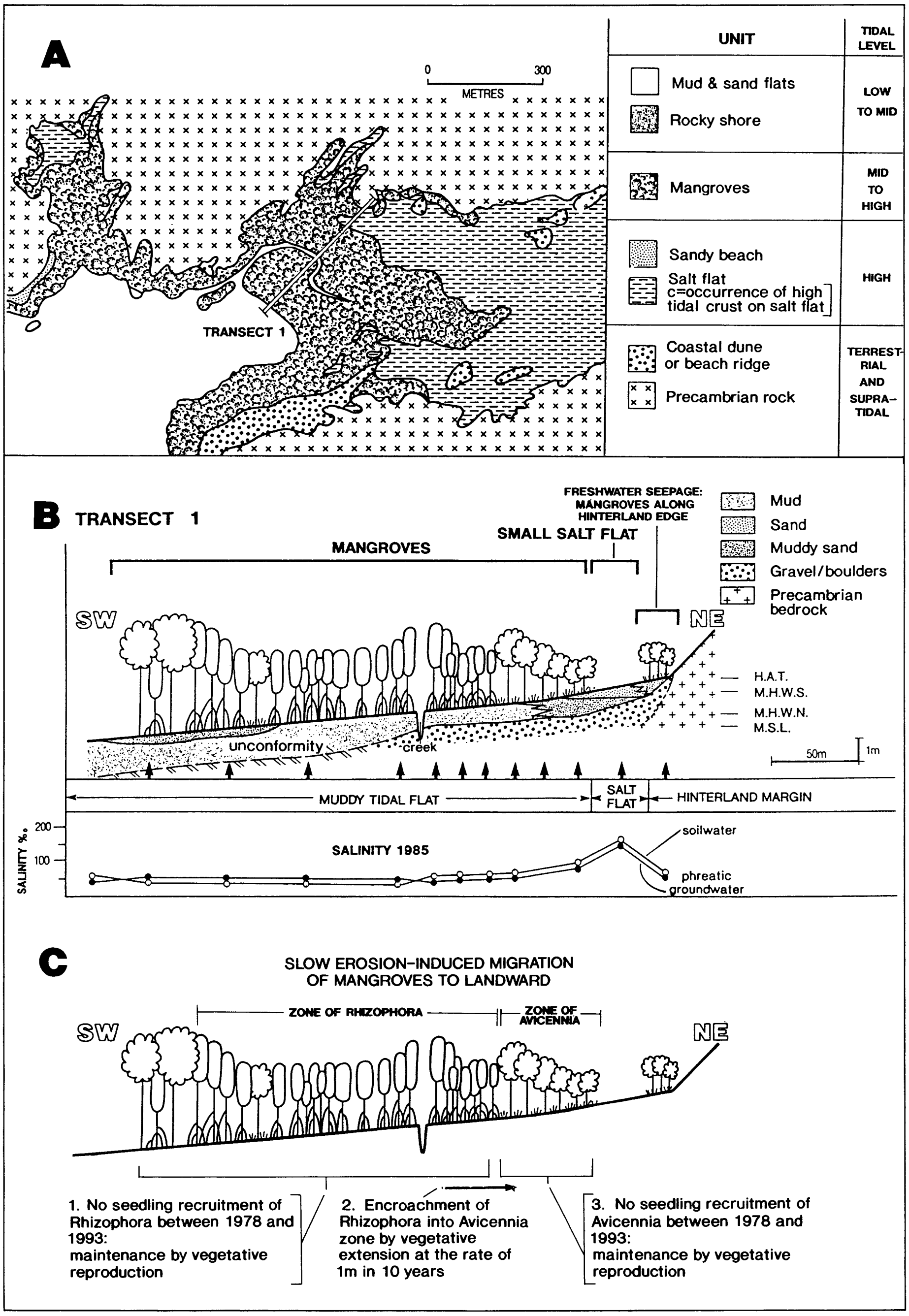


Figure 10. King Bay area in the Dampier Archipelago (see Figure 2E for location. (10A) Distribution of mangroves. (10B) Features of a transect through the mangroves, showing mangrove zonation, stratigraphy, and salinity structure (after SEMENIUK and WURM, 1987). (10C): Mangrove reproductive strategy within the zones, and response of mangroves to slow sheet erosion.

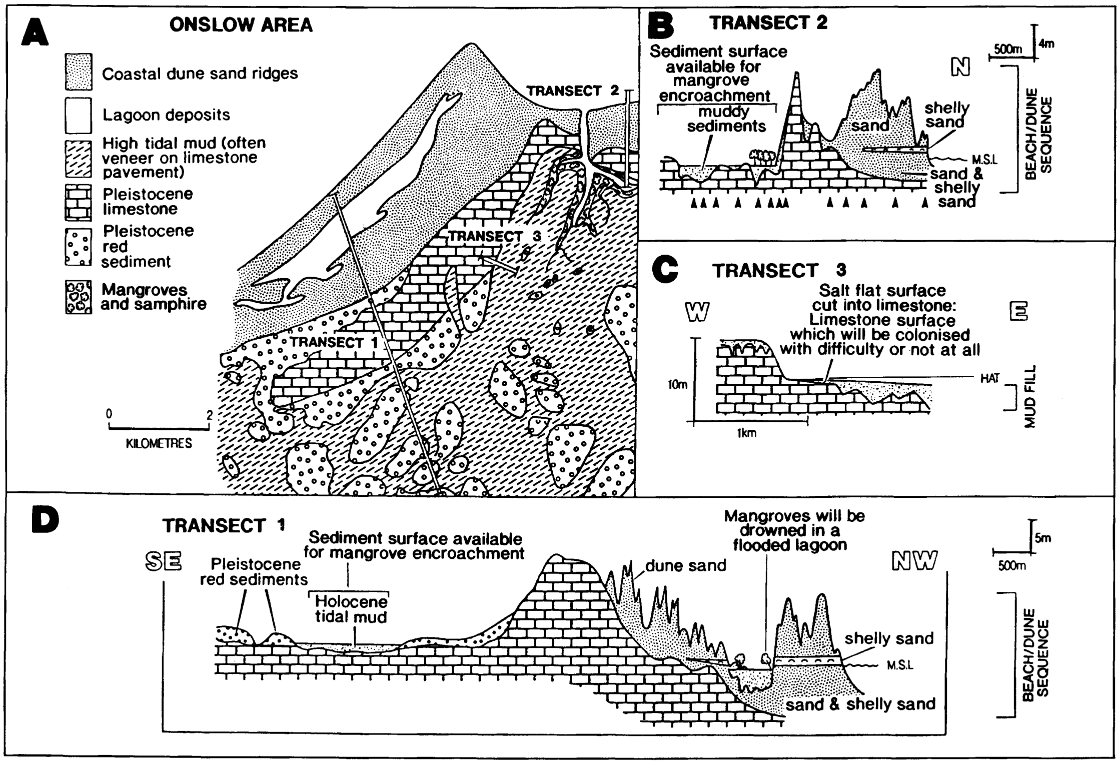


Figure 11. Onslow area, southeastern Pilbara Coast (after SEMENIUK, 1993a). (11A) Geomorphic map of the area. (11B, C and D) Stratigraphic transects, and the potential sites for mangrove encroachment in the event of a sea-level rise.

ments to the new position of sea level will take place (Figure 8).

The Onslow Area

The Onslow area is situated along the southwestern part of the Pilbara Coast sector (SEMENIUK, 1993a). It is a microtidal system set in an arid climate. The coast is fronted by a sandy beach/dune system that mantles an inner system of shore-parallel ridges of Pleistocene limestone. Behind these ridges there is a tidal creek network and extensive salt flats (Figure 11a). Mangroves occur here in two main settings: along the shores/banks of tidal creeks (near Transect 2, Figure 11) and scattered along the shores of a lagoon that is protected from the open ocean. Mangrove vegetation is composed mainly of *Avicennia marina* scrub, but *Rhizophora stylosa* is also present. Where the two occur together, there is distinct zonation: a seaward *Avicennia marina* zone, a middle *Rhizophora* zone, and another landward *Avicennia* zone.

Components of the Onslow area useful for modeling the response of the coast to a sea-level rise are: (1) the salt flat system, and (2) the lagoon system.

Salt flats in the Onslow area are of two types: those comprised wholly of limestone, and those with a veneer of mud over limestone. The former have been eroded from Pleistocene limestone to the level of high-water spring tide by salt weathering (SEMENIUK, 1993a) and are hard pavement surfaces. Mud veneers were formed by Holocene deposition in hollows and depressions in underlying limestone (Figure 11). A sea-level rise would encroach onto these salt flats, and since the area is microtidal, much of the salt flat would be brought within the range of potential mangrove colonisation. However, mangroves will more readily colonise salt flats underlain by mud than those underlain by limestone. There are two reasons for this: first, limestone pavements leave little scope for burrowing benthos to inhabit the mangrove system (and such biota and their burrows are important for mangroves through bioturbation, nutrient recycling and groundwater dynamics (SEMENIUK and WURM, 1987); and second, limestones would provide hard substrates for the mangroves to inhabit. Thus in this case, wide expanses of the salt flat would not readily be colonised by luxuriant and extensive mangroves in case of a rising sea level.

Lagoon systems would have at least two possible responses to a rising sea level. First, the barrier protecting the lagoon could be eroded or overstepped, and the lagoon destroyed. Second, the lagoon could be flooded. The limited exchange through the channel that connects it with the sea would then result in an inundation regime too prolonged or too saline for mangroves to survive. The effect on mangroves of too prolonged a period of inundation as caused by the blockage or restriction of free circulation of seawater (through roadworks, for instance) can lead to mangrove mortality as documented by GORDON (1988). In many localities along the mangrove coasts of Western Australia, inundation in barred environments will result in the death of some existing mangroves, or in the inability of mangroves to further colonise newly formed habitats.

DISCUSSION: ANTICIPATED CHANGES ALONG MANGROVE COASTS OF WESTERN AUSTRALIA DUE TO SEA-LEVEL RISE

The patterns of mangrove distribution in tropical Northwestern Australia provide information useful to predicting the variable effects of sea-level rise on mangroves. Patterns vary in relation to coastal dynamics, habitats, salinity, the sedimentology of tidal flats that are backed by mangroves, the response of mangroves to coastal (sheet) erosion, and the effects of some industrial impacts. Mangrove assemblages and mangrove zones are intimately related to shore profile, soils, habitat stratigraphy and salinity regimes. Any change in these edaphic conditions can lead to alteration of the structure and composition of mangrove systems. A rising sea level will effect some edaphic changes; therefore, coastal ecosystem responses will not be limited to biological ones. For instance, as sea level rises, fundamental changes in soil and salinity regimes are expected, as tidal flat surfaces and groundwaters sedimentologically and hydrologically adjust to new levels of wave base and frequency of inundation.

Predictions of the potential effects of rising sea levels on mangrove systems, or other coastal wetland systems, must address a complex range of issues that include the geomorphic, sedimentologic, hydrologic and biologic nature of the coastal zone (THOM and ROY, 1988; WOODROFFE, 1990; PERNETTA, 1993). The first question is whether a sea level rise into mangrove coasts will result in major, minor or no geomorphic change (Figure 12). Effectively, to some extent, this reflects whether the coast is homogeneous or heterogeneous (Figure 7).

For those coasts that do not undergo major geomorphic change local mangrove populations will only be affected by: (1) the migration of groundwater fields; (2) an increased frequency of inundation on high tidal parts of the tidal zone, and (3) the inundation of barred high-tidal areas. Dependent on the geomorphic and stratigraphic setting, the mangroves may respond with major encroachment landward, or if the substrates are unsuitable, with little encroachment landward.

On the other hand, some areas will undergo major geomorphic changes as the coast, and the various smaller-scale gemorphic units therein, adjust to the new equilibrium position of MSL. These coasts will dramatically alter the mangrove systems because the fundamental nature of the mangrove habitats will be altered. There will be dispersion, or landward migration of existing sand bodies such as spits, dunes and cheniers, as a new wave base is established. A landward transport of muds from the mid-tidal zones will occur, and there may be tidal creek encroachment landwards as tidal waters access the high salt flat and supratidal areas. The response of mangroves to rising sea levels in such systems will be the most difficult to predict because they do not involve simply a mangrove response.

The response of the mangrove coasts will depend on the environmental setting of the mangroves as depicted in Figure 7, which includes an assessment of the tidal range, the stability of the coast, the history of sea level, and the climatic setting. Figure 13 illustrates, in a dichotomous key, a range of possible combinations of the determinative factors that need to be addressed in order to predict the effect of a rising sea level on mangrove coasts. The first hierarchy addresses homogeneity in each coastal type. This determines whether the coast will respond by adjusting geomorphically in a minor or major way. Each coast then can be assessed, in turn, with regards to its tidal range, its accretional or erosional stability, its Holocene sea level history, and its cli-

EFFECTS OF SEALEVEL RISE ON MANGROVE ENVIRONMENTS

NO MAJOR GEOMORPHIC CHANGES	• Increased frequency of inundation (King Sound and King Bay model). • Adjustments of groundwater fields (King Sound model). • Inundation of barred high tidal areas (eg limestone pavements and cemented spits).
MAJOR GEOMORPHIC CHANGES	• Dispersion of sand bodies. • Landward transport of muds. • Tidal creek encroachment.

Figure 12. Effects of a sea-level rise on mangrove coasts.

matic setting. It is suggested that the varied number of responses inherent in this dichotomous approach reflects the potential variable response of mangrove coasts to a rising sea level. Five examples are briefly discussed in Figure 14. In the first three, the coast is homogeneous so that there are no major geomorphic adjustments in the coastal system. Each of the three coasts are in a different climatic setting. In each example, a sea-level rise will cause adjustment and migration of the groundwater salinity regime and an increased frequency of inundation of the high tidal flat.

In the first example, the coast is set in a humid climate, and the mangrove vegetation is species-rich and well zoned. This is typical of many mangrove systems in the Kimberley region of Western Australia. With a sea-level rise, each mangrove zone will respond by migrating landwards by seedling recruitment. Recruitment will occur within the mangrove belt and at its contact with any salt flat at the landward extremity of the mangrove belt.

In the second example, the coast is set in a semi-arid climate; the mangrove vegetation is species-poor and not well zoned; salt flats are present landward of the mangrove belt. This type of coast locally occurs in King Sound and in the Canning Coast region. Following a sea-level rise, the mangrove zone will respond by migrating landwards by seedling recruitment.

In the third example, the coast is set in an arid climate; the mangrove vegetation is species-poor and not well zoned, with a salt flat landward of the mangroves. This type of coast occurs typically in the Pilbara region. Sea-level rising into this sytem will cause the mangrove zones to migrate landwards by vegetative extension since the mangrove populations are maintained by vegetative propagation. This vegetative propagation will occur both within the mangrove belt and at its contact with the salt flat so that mangroves will encroach into the salt flat environment.

The fourth and fifth examples involve heterogeneous coasts. The fourth example illustrates

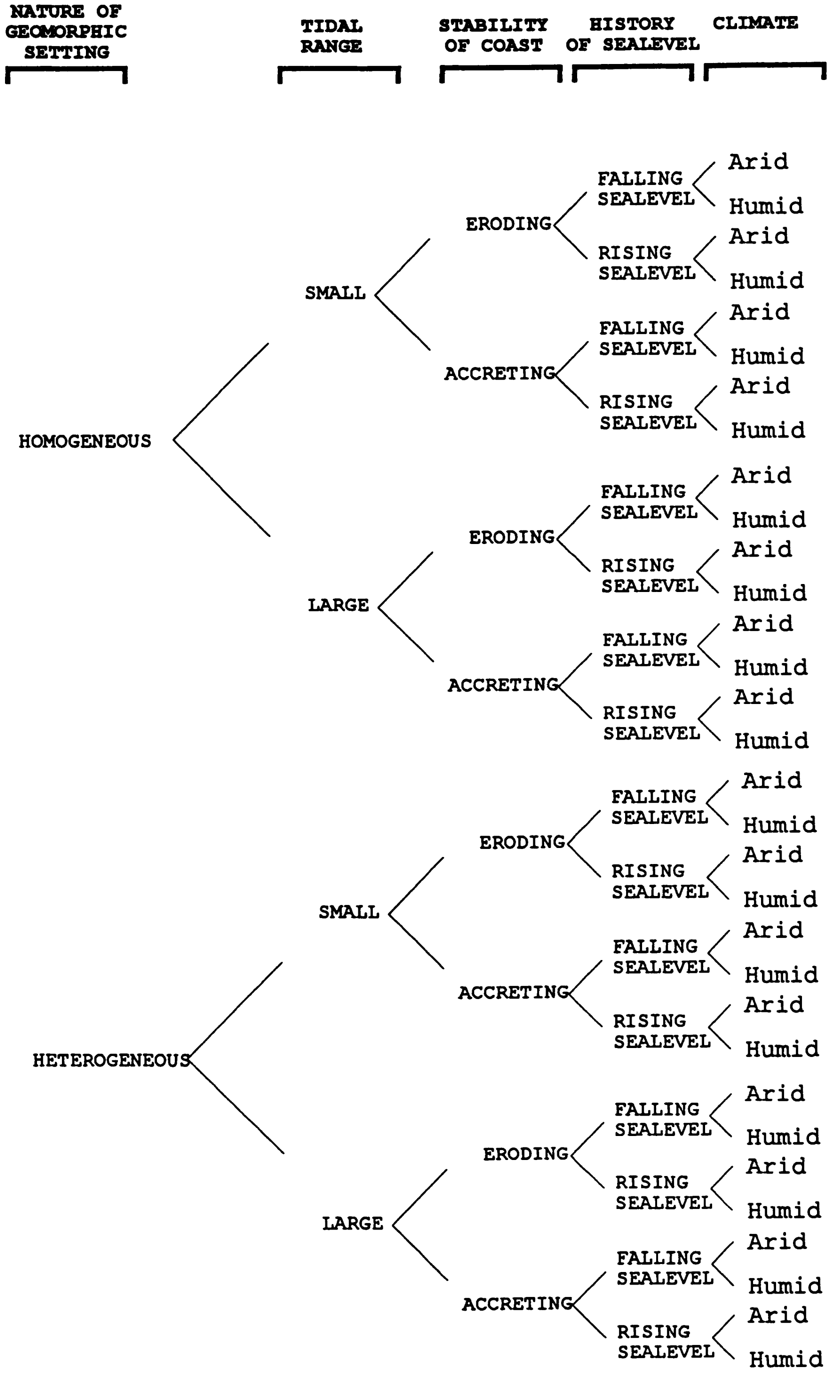


Figure 13. Dichotomous key, drawn from information in Figure 7, to illustrate the range of possible combinations of the factors that will determine the outcome of a sea-level rise on a mangrove coast.

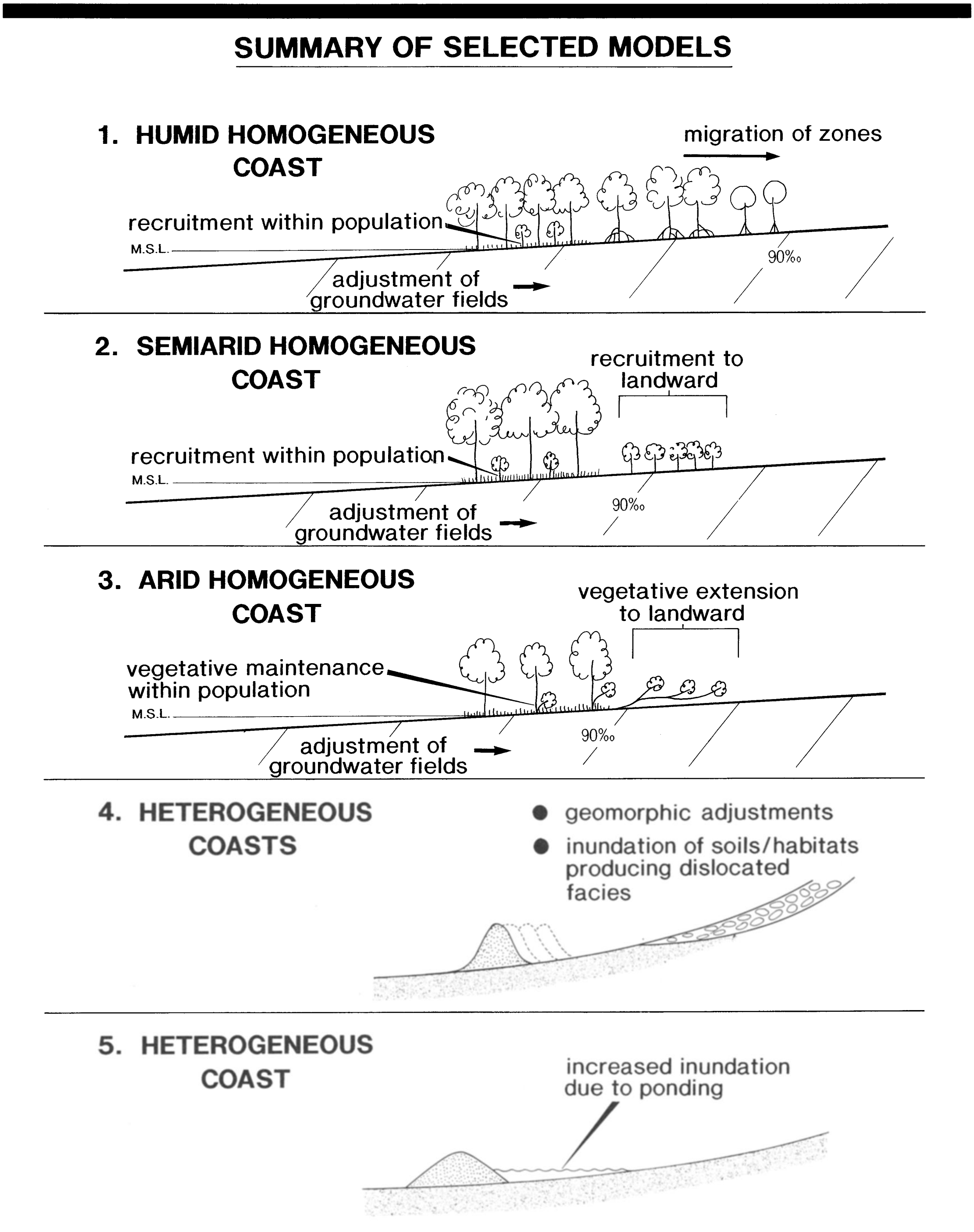


Figure 14. Response of mangrove coasts to a sea-level rise: summary of some selected models.

major geomorphic adjustments, resulting in inundation of soils in mangrove habitats which are now dislocated in relation to their formative sea level. This type of situation typically would occur in the arid Pilbara coast. In the fifth example, the sea-level rise is not followed by any major geomorphic adjustments, but there is increased inundation of a barred lagoon that is fixed behind a cemented bar or barrier.

These examples serve to illustrate that the response of mangrove coasts to a rising sea level will neither be uniform nor simple. Rather it will be varied dependent on the species involved, the type of terrain the sea is rising onto, whether sea-level rise will trigger major geomorphic changes, and the rate of sea-level rise. Given its variability in terms of climate, mangrove biogeography, and coastal types, the Western Australian coast provides an excellent area for studies that predict the effect of sea-level rises on mangroves and other coastal wetland vegetation.

It must be noted that while this paper emphasised the possible effects of a sea-level rise on mangrove coastal systems, it did not explore other related phenomena that may accompany a general global warming. Some of these other changes need to be addressed in conjunction with the effects of a sea-level rise. Many of these changes will directly or indirectly affect mangrove systems biologically, in terms of reproduction and productivity, and physio-chemically, through the alteration of their habitats. These include: anticipated changes in rainfall, evapo-transpiration and wind regimes (to increase wave action and aeolian activity), and increased storminess and incidence of cyclones. Increased evaporation of soil water which may result in increased size of salt flats and increased incidence of storms and cyclones (with their attendant impacts: destruction of mangrove populations and alteration of coastal geomorphology and habitats) are directly related to the predicted effects of a rising sea level because they involve development and maintenance of habitats within the coastal systems.

ACKNOWLEDGEMENTS

I would like to thank C. Woodroffe, C.A. Semeniuk and M. Desbureaux for critically reading the manuscript.

LITERATURE CITED

Bird, E.C.F., 1988. Physiographic indications of a sea-level rise. *In:* G.I. Pearman (ed.), *Greenhouse: Planning for Climate Change,* pp. 60–73. Australia: Commonwealth Scientific & Industrial Research Organisation. 752p.

Brown, R.G., 1976. Exmouth Gulf. *In:* Logan, B.W.; Brown, R.G., and Quilty, P.G. (eds.), Carbonate Sediments of the West Coast of Western Australia. *25th International Geological Congress* (Sydney) 1976, pp. 55–75.

Bureau of Metereology, 1975. *Climatic Averages: Western Australia.* Canberra: Australian Government Publishing Service.

Chapman, V.J., 1976. *Mangrove Vegetation.* Lehre: Cramer, 447p.

Cintron, G.; Lugo, A.E.; Pool, D.J., and Morris, G., 1978. Mangroves of arid environments in Puerto Rico and adjacent islands. *Biotropica* 10, 110–121.

Coleman, F., 1971. *Frequencies, Tracks and Intensities of Tropical Cyclones in the Australian Region, November 1909-June 1969.* Bureau of Meterology, Canberra: Australian Government Public Service, 42p.

Daniels, R.C.; Gornitz, V.M.; Mehta, A.J.; Lee, S.C., and Cushman, R.M., 1992. Adapting to sea-level rise in the U.S. Southeast: the influence of built infrastructure and biophysical factors on the inundation of coastal areas. *Environmental Sciences Division Publication No. 3915,* Oakridge, Tennessee: Oak Ridge National Laboratory, ORNL/CDIAC-54.

Davies, J.L., 1977. The coast. *In:* Jeans, D.N. (ed.), *Australia, A Geography,* Sydney: Sydney University Press, pp. 134–151.

Davis, J.H., Jr., 1940. The ecology and geological role of mangroves in Florida. *Papers from Tortugas Lab 32.* Washington D.C.: Carnegie Institute Washington Publication, 517, 305–412.

Easton, A.K., 1970. The tides of the continent of Australia. *Horace Lambert Center Oceanographic Research Research Paper No. 37.* Flinders Univ (SA).

Gentilli, J., (ed.), 1971. Climates of Australia and New Zealand. *World Survey Climatology 13* (Elsevier), 405p.

Gentilli, J., 1972. *Australian Climate Patterns.* Sydney: Nelson, 285p.

Geological Survey of Western Australia, 1976. The geology of Western Australia. Perth: *Geological Survey of W.A. Memoir 2.*

Gordon, D.M., 1988. Disturbance to mangroves in tropical-arid Australia: hypersalinity and restricted tidal exchange as factors leading to mortality. *Journal Arid Environments* 15, 117–145.

Gornitz, V.; Lebedeff, S., and Hansen, J., 1982. Global sea level trend in the past century. *Science,* 15, 1612–1614.

Hine, A.C.; Belknap, D.F.; Hutton, J.G.; Osking, E.B., and Evans, M.W., 1988. Recent geological history and modern sedimentary processes along an incipient, low-energy, epicontinental-sea coastal: northwest Florida. *Journal of Sedimentary Petrology* 58, 567–579.

Hoffman, J.S., 1984. Estimates of future sea level rise. *In:* Barth, M.C. and Titus, J.G. (eds.), *Greenhouse Effect and Sea Level Rise,* pp. 79–103. New York: Van Nostrand Reinhold, 325p.

Jennings, J., 1975. Desert dunes and estuarine fill in the Fitzroy estuary, northwestern Australia. *Catena* 2, 215–262.

JENNINGS, J. and BIRD, E.C.F., 1967. Regional geomorphological characteristics of some Australian estuaries. *In:* LAUFF, G.H. (ed.), *Estuaries.* American Association for Advanced Science, 121–128.

JOHNSON, D.P., 1982. Sedimentary facies of an arid zone delta: Gascoyne, delta, Western Australia. *Journal of Sedimentary Petrology* 52, 547–563.

KLEIN, G., DEV., 1985. Intertidal flats and intertidal sand bodies. *In:* DAVIES, R.A., JR. (ed.), *Coastal Sedimentary Environments.* New York: Springer-Verlag, pp. 187–224.

KNIGHTON, A.D.; WOODROFFE, C.D., and MILLS, K., 1992. The evolution of tidal creek networks, Mary River, northern Australia. *Earth Surface Processes on Landforms* 17, 167–190.

LEPROVOST SEMENIUK and CHALMER P/L, 1982. Recovery monitoring: an investigation of natural adjustments of the high tidal environment at Spoil Area No. 4. Unpublished consultant report to Woodside Offshore Petroleum Pty. Ltd. (Report publically available through E.P.A., Perth, Western Australia).

LOGAN, B.W.; READ, J.F., and DAVIES, G.R., 1970. History of carbonate sedimentation, Quaternary Epoch, Shark Bay, Western Australia. *In:* Carbonate sedimentation and environments, Shark Bay, Western Australia. Tulsa, Oklahoma: *American Association of Petroleum Geologists Memoir 13,* pp. 38–84.

LOURENSZ, R.S., 1981. *Tropical Cyclones in the Australian Region, July 1909 to June 1980.* Canberra: Bureau Meteorology, Australian Government Publication Service, 94p.

LUGO, A.E. and SNEDAKER, S.C., 1974. The ecology of mangroves. *Annual Review of Ecology and Systematics,* 5, 39–64.

MACNAE, W., 1968. A general account of the fauna and flora of mangrove swamps and forests in the Indo-West-Pacific region. *Advances in Marine Biology* 6, 73–270.

MASSELINK, G. and SHORT, A.D., 1993. The effect of tide range on beach morphodynamics and morphology. *Journal Coastal Research,* 9, 785–800.

MILTON, D., 1978. The rainfall from tropical cyclones in West Australia. *Geowest. Working Papers,* Department of Geography, University of Western Australia 13, 61p.

ORSON, R.; PANAGEOTOU, W., and LEATHERMAN, S.P., 1985. Response of tidal salt marshes to rising sea levels along the U.S. Atlantic and Gulf coasts. *Journal Coastal Research,* 1, 29–37.

PARKINSON, R.W., 1989. Decelerating Holocene sea-level rise and its influence on southwest Florida coastal evolution: a transgressive/regressive stratigraphy. *Journal Sedimentary Petrology,* 59, 960–972.

PARKINSON, R.W.; DELAUNE, R.D., and WHITE, G.R., 1994. Historical and geological mangrove peat accretion rates and their use in sea-level rise forecasting models. *Journal Coastal Research,* 10(4).

PEARMAN, G.I. (ed.), 1988. *Greenhouse: Planning for Climate Change.* Commonwealth Scientific and Industrial Research Organisation (Australia), 752p.

PERNETTA, J.C., 1993. Mangrove forests, climate change and sea level rise: hydrological influences on community structure and survival, with examples from the Indo-West Pacific. *A Marine Conservation and Development Report.* IUCN (Gland, Switzerland) ISBN 2-8317-0183-X.

SAENGER, P.; SPECHT, M.M.; SPECHT, R.L., and CHAPMAN, V.J., 1977. Mangal and coastal salt marsh communities in Australasia. *In:* CHAPMAN, V.J. (ed.), *Ecosystems of the World. 1. Wet Coastal Ecosystems.* Amsterdam: Elsevier, 293–345.

SCHOLL, D.W., 1964. Recent sedimentary record in mangrove swamp and rise in sea level over the southwestern coast of Florida: Part 2. *Marine Geology,* 2, 343–364.

SCHOLL, D.W. and STUIVER, M., 1967. Recent submergence of south Florida: a comparison with adjacent coasts and other eustatic data. *Geological Society of America Bulletin* 78, 437–454.

SEMENIUK, V., 1980a. Mangrove zonation along an eroding coastline in King Sound, North-Western Australia. *Journal Ecology,* 68, 789–812.

SEMENIUK, V., 1980b. Quaternary stratigraphy of the tidal flats King Sound, Western Australia. *Journal Royal Society of Western Australia,* 63, 65–78.

SEMENIUK, V., 1981a. Long-term erosion of the tidal flats King Sound, North-Western Australia. *Marine Geology,* 43, 21–48.

SEMENIUK, V., 1981b. Sedimentology and the stratigraphic sequence of a tropical tidal flat, North-Western Australia. *Sedimentary Geology,* 29, 195–221.

SEMENIUK, V., 1983. Regional and local mangrove distribution in Northwestern Australia in relationship to freshwater seepage. *Vegetatio,* 53, 11–31.

SEMENIUK, V., 1985. Development of mangrove habitats along ria coasts in north and northwestern Australia. *Vegetatio,* 60, 3–23.

SEMENIUK, V., 1986. Terminology for geomorphic units and habitats along the tropical coast of Western Australia. *Journal Royal Society of Western Australia,* 68, 53–79.

SEMENIUK, V., 1993a. The Pilbara coast: a riverine coastal plain in a tropical arid setting, northwestern Australia. *In:* WOODROFFE, C.D. (ed.), Late Quaternary evolution of coastal and lowland riverine plains of southeast Asia and northern Australia. *Sedimentary Geology* 83, 235–256.

SEMENIUK, V., 1993b. The mangrove systems of Western Australia—Presidential address. *Journal Royal Society of Western Australia,* 76, 99–122.

SEMENIUK, V. (in preparation). The maintenance of populations of *Avicennia marina* and *Rhizophora stylosa* along the arid Pilbara coast, northwestern Australia.

SEMENIUK, V.; KENNEALLY, K.F., and WILSON, P.G., 1978. Mangroves of Western Australia. *Handbook 12,* Perth: West Australian Naturalists Club Perth, 90p.

SEMENIUK, V. and WURM, P.A.S., 1987. Mangroves of the Dampier Archipelago, Western Australia. *Journal Royal Society of Western Australia,* 69, 29–87.

SPACKMAN, W.; RIEGL, W.L., and DOLSEN, C.P., 1964. Geological and biological interactions in the swamp-marsh complex of southern Florida. *In:* DAPPLES, E.C. and HOPKINS, M.E. (eds.). Environments of coal deposition. *Geological Society of America, Special Paper,* 114.

SPECHT, R.L., 1981. Foliage projective cover and standing biomass. *In:* GILLSON, A.N. and ANDERSON D.J.

(eds.), *Vegetation Classification in Australia*. Canberra: CSIRO & ANU Press.

STEEDMAN, R.K., 1985. Air quality meteorology of the Burrup Peninsula, Western Australia, June 1982 to December 1984. Vol. 1 text and appendices A to G. *R.K. Steedman Ltd. Report no. R271 August 1985*, Unpublished Report to Woodside Offshore Petroleum Ltd.

STEEDMAN, R.K. and COLMAN, E.J., 1985. On the joint probability of extreme winds, waves and currents at North Rankin 'A', north western Australia. *In:* The application of joint probability of Metocean phenomena in the oil industry's structural design work. *The Oil Industry International Exploration & Production Forum* (London).

THOM, B.G. and ROY, P.S., 1988. Sea-level rise and climate: lessons from the Holocene. *In:* PEARMAN, G.I. (ed.), *Greenhouse: Planning for Climate Change*, pp. 177–188. Commonwealth Scientific and Industrial Research Organisation (Australia), 752p.

THOM, B.G.; WRIGHT, L.D., and COLEMAN, J.M., 1975. Mangrove ecology and deltaic-estuarine geomorphology. *Journal of Ecology* 63, 203–232.

TOMLINSON, P.B., 1986. *The Botany of Mangroves*. Cambridge: Cambridge University Press, 413p.

VANDERZEE, M.P., 1988. Changes in saltmarsh vegetation as an early indicator of sea-level rise. *In:* PEARMAN G.I. (ed.), *Greenhouse: Planning for Climate Change*, Commonwealth Scientific & Industrial Research Organisation, pp. 147–160.

WELLS, A.G., 1981. A survey of riverside mangrove vegetation fringing tidal river systems of Kimberley, Western Australia. *In:* Biological Survey of Mitchell Plateau and Admiralty Gulf, Western Australia. *Western Australia Museum Supplement No. 3* (Perth), pp. 95–121.

WELLS, A.G., 1982. Mangrove vegetation of northern Australia. *In:* CLOUGH, B.F. (ed.), *Mangrove Ecosystems in Australia: Structure, Function and Management*. AIMS and ANU Press, pp. 57–78.

WOODROFFE, C.D., 1990. The impact of sea-level rise on mangrove shorelines. *Progress. Physical Geography* 14, 483–520.