Technical Report

The Coast of the Shires of Shark Bay to Exmouth, Gascoyne, Western Australia:
Geology, Geomorphology and Vulnerability

December 2012

GOVERNMENT OF WESTERN AUSTRALIA
Department of **Planning**
Department of **Transport**

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Cover Photographs
Top-left:
Perched beach at Vlamingh Head (Photograph: Bob Gozzard. May 2011).
Top-right:
Climbing dune on the Ningaloo coast (Photograph: Bob Gozzard. May 2011).
Bottom-left:
Coral Bay (Photograph: Bob Gozzard. May 2011).
Bottom-right:
Gascoyne River delta at Carnarvon (Photograph: Ian Eliot. May 2011).

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EXECUTIVE SUMMARY

The key aim of this project was to determine the vulnerability of landforms along the Gascoyne coast to changing environmental conditions, including projected changes in climate. The determination involved site visits, assessment of aerial photography, a review of available meteorologic and oceanographic information and land system mapping of coastal land systems between Murchison River and Locker Point. Landforms were considered in detail for Areas of Planning Interest including populated and proposed development sites. Interpretation of the information gathered was intended to identify vulnerable locations within the Study Area and assist decision-making regarding the location of any proposed coastal development and for coastal management purposes.

The Gascoyne coast is mainly an inherited coast with many coastal landforms reflecting historic environmental conditions, often hundreds or thousands of years before present. There is limited availability of sediment along the coast, with the exception of silty sands supplied by the Gascoyne River distributed between the river mouth and Point Quobba. A result of the limited sediment availability is that coastal variability is largely constrained by the rocky framework and old landforms forming its inherited structure. Conversely, on those sections of the coast where sediment supply is effectively unrestricted, landform changes are highly variable and readily adjust to fluctuations in environmental conditions. This includes variation of sediment supply, with the Gascoyne River delta responding in a cyclic fashion after runoff flooding.

The Gascoyne coast marks a transitional zone for environmental conditions. At its southern end, the coast is influenced by mid-latitude synoptic systems and microtidal diurnal conditions. Northwards, there is increasing influence of tropical synoptic systems, with increased influence of semi-diurnal tides and larger tidal range. There are further regional variations in metocean processes due to the influence of the inner shelf and gulf structures at different spatial scales. These determine whether coastal variability is constrained by the geologic framework or if there is a stronger relationship between landform structures and environmental conditions.

Features along the Gascoyne coast suggest the variability of coastal processes across the region. Sediment is most abundant between Carnarvon and Point Quobba, fed by a large but irregular supply from the Gascoyne River. Elsewhere, sediment is less readily available. The Zuytdorp Cliffs indicate a general deficit of sediment in the nearshore north of the Murchison River. Sediment supply from the Wooramel and Yannarie river systems is moderate to low and highly irregular with active coastal processes mainly consisting of sediment reworking of the mudflats. These low-lying environments are highly susceptible to extreme metocean events; particularly river flooding resulting from high rainfall during cyclonic events and marine inundation due to storm surge and fluctuation in sea levels. Bioproduction on subtidal terraces in Shark Bay and on coral reefs in Ningaloo locally contributes some sediment to inshore waters and the shore. Again these sources are markedly affected by metocean processes and sediment may be lost to deeper water offshore.

Approach

In any coastal environment some coastal features are more vulnerable to climate and sea level variation than others. Along the Gascoyne coast, where sediment availability is limited, coastal landforms largely inherited from the geological past and landform changes are constrained by the rocky framework. The vulnerability of different parts of the coast is likely to be highly variable. Intuitively, areas where rock outcrops or supports unconsolidated sediments above high water level are likely to be less vulnerable than low-lying sandy or muddy shores. However, vulnerability also depends on other factors, such as hardness of the rock, the current stability of the landforms it supports and extreme weather and oceanographic processes affecting the shore. Hence landform vulnerability was estimated as a combination of the susceptibility of the geological structure supporting the landforms to environmental change and the current condition of the landforms as indicated by existing evidence of erosion. Together, a geological structure and the landforms it supports define a land system. The assessment involved consideration of the integrity of the geological or geomorphologic structures of land systems, their susceptibility to change, and the condition or stability of the landforms they support. The analysis was intended to be indicative rather than prescriptive, with applications for strategic planning purposes a first step to more detailed risk assessment procedures.

Bedrock geological control, land systems and metocean processes were used to identify discrete coastal compartments and sediment cells. Changes to land systems and landforms in one part of a compartment or cell were highly likely to affect adjoining landforms within the compartment or cell but with potentially limited affect on adjoining compartments or cells. Vulnerability ratings were then estimated for the coastal compartments and sediment cells. The Gascoyne coast comprises seven primary, twenty four secondary compartments and forty eight tertiary compartments. In its northern reaches the Study Area partly extends into an eighth primary compartment, the Eastern Gulf which includes the Yannarie salt flats. The vulnerability of the seven complete primary compartments, including the Zuytdorp, Freycinet, L'Haridon, Gascoyne, MacLeod, Ningaloo and Western Gulf compartments has previously been considered for strategic planning. They were not considered at this scale further in this report.

Secondary compartments were considered at a land system scale appropriate to strategic planning. Land systems for the twenty four secondary compartments were identified, mapped and their geology, geomorphology and landforms described. Tertiary compartments were not considered in this study, given its dual focus on broad strategic planning and local area planning.

Sediment cells of the Gascoyne coast were considered in detail at a landform scale appropriate to local area planning for fifteen Areas of Planning Interest. The Areas of Planning Interest included fifteen primary sediment cells and five secondary sediment cells, providing an incomplete coverage of the Study Area. The landforms for each sediment cell were identified, mapped and described at a finer spatial scale than that used to describe the secondary compartments.

The analysis was intended to be indicative rather than prescriptive and has application for strategic planning purposes as a first step to more detailed risk assessment procedures.

Land System Susceptibility

Susceptibility rankings were determined from values assigned to marine topography on the inner continental shelf and near the shore; the shape of the shoreline; coastal orientation; and the prevailing landform types present in the secondary compartment or sediment cell under consideration.

Seventeen of the 24 (71%) secondary compartments had a low susceptibility. Five secondary compartments (21%) were moderately susceptible and two (8%) were highly susceptible. Secondary compartments had low susceptibility where the coast was protected by a nearly continuous offshore reef or a wide shelf; there was a wide sub-tidal terrace or bank; rock outcrops with some cliffs and bluffs outcrop along the shore; the coast was sheltered from metocean forcing; beaches were perched on an intertidal rock surface; and/or the dune barrier was likely to be perched on a rock surface above the highest astronomic tide.

The areas with low susceptibility were the:

- Zuytdorp cliffs with narrow a continental shelf, including two compartments between Nunginjay Spring Coast North and Cape Inscription;
- Six compartments within Shark Bay between Cape Bellefin and Nilemah Coast East with wide sub-tidal terraces underpinned by the geologic framework;
- Wooramel Bank with a wide sub-tidal terrace, inherited deltaic features and tidal flats, including two compartments from Nilemah Coast East to Grey Point;
- Five compartments along Ningaloo coast from Cape Cuvier to North West Cape with the exception of the highly susceptible Point Cloates to Winderabandi Point. The five have shallow coral reefs, inshore lagoons, bluffs, perched dunes and arcuate coasts; and
- Western Exmouth Gulf, including two compartments extending from Northwest Cape to Giralia that are partially sheltered from swell and have sub-tidal terraces, receded barriers, rocky coasts and some inherited deltaic features in the south.

Secondary compartments considered moderately susceptible to change were exposed to metocean forcing; had unconsolidated landforms; part of active river deltas; and lack bedrock support or offshore reefs were not common in the Study Area. The moderately susceptible secondary compartments were:

- Murchison River to Nunginjay Spring Coast North with a westerly aspect, deep intermittent reef and a source of sediment from the Murchison River;
- Cape Inscription to Cape Bellefin on eastern Dirk Hartog Island with unconsolidated inshore sediments, a northerly aspect and no barrier;
- South Bejaling Hill to Point Quobba with shallow intermittent reef, high exposure, beach rock and dunes above high tide level;
- Point Quobba to Cape Cuvier with extensive platforms and cliffs on an exposed coast with deep inshore bathymetry; and
- Giralia to Locker Point with inherited deltaic features and wide tidal flats.

The two tracts of coast highly susceptible to change in the natural structure were Grey Point to South Bejaling Hill, part of the active Gascoyne River delta; and Point Cloates to Winderabandi Point with a westerly aspect, cuspate forelands and a sandy shoreface.

Landform Stability

Instability rankings were based on the proportion of rocky versus sandy seabed; number of tidal creeks per 10km of shoreline; beachface shape; whether the frontal dune complex had been eroded; an overall estimate of vegetation cover on sand barriers and the characteristics of tidal flats.

Relatively stable secondary compartments displaying low instability occurred where the coast had a limited amount of sediment stored inshore with sheltering by inshore reefs and/or rocky pavement; sandy beachface was either not present, perched on rock or had a sheltered profile; the frontal dune complex was relatively intact or perched on rock above highest astronomic tide; the barrier dunes were well vegetated; and/or they had vegetated tidal flats with few tidal creeks or a continuously lithified chenier ridge. Most secondary compartments, 17 of the 24 (71%) had a low instability, which is to say they were stable compared to other compartments in the region. Five secondary compartments (21%) were moderately unstable and two (8%) were highly unstable.

Areas with low landform instability were the:

- Zuytdorp cliffs without a barrier or beach, including two compartments extending between Nunginjay Spring coast N and Cape Inscription;
- Shark Bay compartments, including six between Cape Bellefin and Nilemah Coast East. The compartments had sheltered sandy beaches perched on inshore rock platforms and discontinuous or partly scarped foredunes.
- Southern Wooramel Bank, from Nilemah Coast East to Wooramel Coast ,with inshore rock pavement, sheltered beachfaces and moderately stable tidal flats;
- Ningaloo coast from Point Quobba to North West Cape with the exception of the moderately-unstable Point Cloates to Winderabandi Point, included six secondary compartments. It had sheltered beachfaces perched on inshore rock and was in the lee of reef, had less than 25% active dunes and some frontal dune scarping; and
- Western Exmouth Gulf, including two secondary compartments between Northwest Cape and Giralia, with sheltered beachfaces perched on inshore rock and moderately stable foredunes.

Secondary compartments with moderately unstable landforms were not common in the Study Area. Combinations of some of the following factors indicated present levels of landform instability: the inshore seabed containing more bare sand; beaches commonly subject to higher wave conditions or river activity; there were fewer foredunes and the frontal dune may have been cliffed; vegetation cover was low and mobile dunes were present on the barrier; and tidal flats had less vegetation and more tidal creeks.

The moderately unstable secondary compartments were:

- Cape Inscription to Cape Bellefin on eastern Dirk Hartog Island with bare sand surfaces in the inshore;
- Wooramel Coast to Grey Point with bare sand in the inshore and tidal flats with many tidal creeks and limited vegetation landward of the area affected by surge;
- Grey Point to South Bejaling Hill with contemporary sediment supplied by the Gascoyne River and reworking of these and older sediments across the inshore, beachface, foredunes and frontal dunes;
- Point Cloates to Winderabandi Point, which had bare sand surfaces inshore of reef, more exposed beaches and active foredunes, frontal dunes and mobile dunes; and
- Giralia to Locker Point, where there were bare tidal flats with many tidal creeks and limited vegetation.

Two tracts of coast with highly unstable landforms were the two compartments immediately north of active river systems, the Murchison and the Gascoyne Rivers. The compartments were: Murchison River to Nunginjay Spring Coast North with an exposed perched beach on shallow pavement, scarped frontal dune and a source of sediment from the Murchison River to the south; and South Bejaling Hill to Point Quobba with less than 25% reef with a source of sediment from the Gascoyne River to the south, exposed beaches, low frontal dune vegetation cover and some mobile dunes.

Vulnerability

Difference between the rankings for susceptibility and instability assigned to the same compartment were notable and highlight the significance of long-term versus short-term change. These were factors that were drawn together in determination of vulnerability which is expressed as a combination of landform association susceptibility to change due to metocean forcing and landform instability. A compartment or cell ranked at one level s highly likely to contain components of susceptibility and/or instability ranked at another. In particular, a compartment or cell ranked at a moderate level may have elements that are highly susceptible to change in the metocean regime and/or has landforms that are currently unstable. The qualification is particularly important at increasingly broader spatial scales in the land system hierarchy where a wider range of land systems and landforms is included at each compartmental scale.

The majority of the secondary compartments, 16 of the 24 (67%) had a low vulnerability. Two secondary compartments (8%) had low-to-moderate vulnerability, two (8%) had moderate vulnerability, four (17%) had a moderate-to-high vulnerability and none had a high vulnerability.

Secondary compartments with low vulnerability were those with less susceptible natural structural features and low landform instability. The areas with low vulnerability, where coastal risk is unlikely to be a constraint to coastal management at a secondary compartment scale, were the:

- Zuytdorp cliffs, including the two compartments from Nunginjay Spring Coast North to Cape Inscription;

- Shark Bay, including the six compartments from Cape Bellefin to Nilemah Coast East;
- Southern Wooramel Bank , extending from Nilemah Coast East to Wooramel Coast;
- Ningaloo coast, including the five compartments from Cape Cuvier to North West Cape but with the exception of Point Cloates to Winderabandi Point which had a moderate-to-high vulnerability; and
- Western Exmouth Gulf, with two compartments between Northwest Cape and Giralia.

The secondary compartments with low-to-moderate vulnerability were those with less susceptible natural structural features or low landform instability. They were areas where coastal risk is likely to present a low constraint to coastal management at a secondary compartment scale. The two compartments were Wooramel coast to Grey Point with moderate instability associated with active inshore sediments and tidal flats; and the exposed Point Quobba to Cape Cuvier with moderate susceptibility associated with deep inshore bathymetry and extensive platforms and cliffs.

Secondary compartments of the Gascoyne coast with moderate vulnerability were those with moderately susceptible natural structural features and moderate landform instability. These are areas where coastal risk may present a moderate constraint to coastal management at a secondary compartment scale. The two compartments were Cape Inscription to Cape Bellefin with unconsolidated sediments active in the inshore, a northerly aspect and no barrier; and Giralia to Locker Point with wide tidal flats with inherited deltaic features, many tidal creeks and limited vegetation landward of the area affected by surge.

The secondary compartments with moderate-to-high vulnerability were those with highly susceptible natural structural features or high landform instability. These were areas where coastal risk is likely to be a significant constraint to coastal management at a secondary compartment scale. The two compartments highly susceptible to change were associated with mobile structures on the active Gascoyne River delta between Grey Point and South Bejaling Hill and the cuspate forelands from Point Cloates to Winderabandi Point. The two compartments with highly unstable landforms were immediately north of active river systems, they extend from the Murchison River to Nunginjay Spring Coast North immediately north of the Murchison River and from South Bejaling Hill near the Gascoyne River to Point Quobba.

Twenty sediment cells were considered. Four cells ranked as low vulnerability, seven as low-to-moderate, six as moderate, none as moderate-to-high and three as high vulnerability. Many of the cells had a higher vulnerability ranking when considered at a finer spatial scale than the secondary compartments because the areas of higher coastal risk represented a higher proportion of the coast of interest. Higher coastal risk could be attributed to a higher proportion of susceptible natural structural features, such as cuspate forelands, and/or more unstable landforms, such as active dunes and scarped foredunes.
A more detailed assessment of the vulnerability of each area was completed at a sediment cell scale.

Fifteen Areas of Planning Interest were identified for the Shires of Shark Bay to Exmouth. The more detailed vulnerability assessment for each Area of Planning Interest included the the susceptibility, instability and vulnerability rankings; identification of the landforms most at risk and other coastal constraints related to metocean forcing; advice for coastal management; and identification of relevant further studies. The fifteen Areas of Planning Interest included:

- Nanga
- Denham
- Little Lagoon
- Monkey Mia
- Carnarvon
- Miaboolya Beach
- Blowholes
- Quobba Station
- Red Bluff
- Three Mile Camp
- Gnaraloo Station
- Gnaraloo Bay
- Coral Bay
- Vlamingh Head
- Exmouth.

Overview

The Gascoyne coast contains a broad range of coastal types, for which existing planning policies provide an equally broad range of vulnerability assessment techniques, and often suggest case-by-case evaluation. The application of simple conceptual models, such as *Schedule One* of the State Coastal Planning Policy, produces a highly varied risk profile, in which the results more strongly reflect the applicability of the model than anticipated coastal dynamics. Due to the complexity and variability of the Gascoyne coast, there are numerous locations in which secondary processes, neglected in a simple model, are dominant. Coast types where existing planning policies are difficult to implement directly are prevalent across the Gascoyne, including mixed sand and rock coast, large river deltas or low-lying tidal flat morphology. Consequently, an approach was developed, assessing coastal vulnerability based on land system and landform information. The approach used published descriptions of the relative susceptibility of coastal land systems to respond to metocean processes variability; as well as the present stability of individual landforms comprising them.

Susceptibility of coastal land systems is defined by structural characteristics, including materials, and encompasses the capacity for coastal change to reach critical thresholds or tipping points. Susceptible systems are usually affected by gradual environmental changes. Instability relates to the degree to which landforms are responsive to short-term environmental variability, and captures the cyclic or progressive nature of disturbance and recovery. The technique of combining inherent structural susceptibility and observed instability aims to account for both gradual and rapid responses to environmental change. Along the Gascoyne coast, extensive geologic and geomorphic inheritance commonly causes dissociation between susceptibility and instability. This has implications for the use of *Schedule One* of the State Coastal Planning Policy, which is strongly tied to modern observations and therefore provides an indication of instability only.

The vulnerability analysis provides a foundation for more extensive risk assessments which could identify the processes of change in more detail; examine social and economic implications; determine the consequences of projected and existing patterns of coastal change; and plan and implement adaptation strategies. To some extent, some of the adaptation strategies are embedded in the *Coastal Zone Management Policy for Western Australia,* which provides the principles and rationale for advice arising from examination of vulnerability on the Gascoyne coast.

Compartments or cells with a high vulnerability ranking were areas where the potential effect of metocean processes was considered a major constraint to development due to weakness of the natural structures or poor natural resilience. These areas potentially require high ongoing management requirements and typically are suitable for limited development. Sufficient justification to address major constraints usually occurs only if there is a very strong economic and social imperative, such as large-scale infrastructure requiring coastal access for marine-based industries, major harbours or port facilities. Detailed investigations are recommended as the basis for establishment of such infrastructure, including geotechnical studies (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique), sediment budget analysis (approximate volumetric rates of sediment transport including sources and sinks) and numerical modelling (such as wave, current and sediment transport modelling to provide further context for the volumetric rates of sediment transport).

Lower levels of estimated vulnerability for each compartment or cell identify more specific constraints to potential land use and whether the constraint is linked to long-term susceptibility to landform change or short-term instability. In general, susceptibility requires engineering intervention to alleviate potential problems whereas instability is commonly addressed by less obtrusive management including the use of coastal setback to development.

Assessment within each of the Areas of Planning Interest has illustrated that there are significant challenges to the synthesis of existing studies and plans across the Gascoyne Region. In many cases, studies describing observed change or projecting potential change are preliminary or basic in nature, with few recognising the inherited nature of many coastal landforms. The relative absence of planning criteria for developed areas has, in some cases, resulted in an inconsistent application of coastal planning and coastal risk mitigation. This is well illustrated by a lack of consideration of coastal hazards within the Red Bluff Masterplan and failure to translate engineering requirements for hazard mitigation into planning for Coral Bay.

WEB SUMMARY

The aim of this project was to determine the vulnerability of landforms along the Gascoyne coast to changing weather and oceanographic conditions, including projected changes in climate. The Gascoyne coast is mainly an inherited coast. There is limited availability of sediment along the coast, with the exception of silty sands supplied by the Gascoyne River to the coast between the river mouth and Point Quobba at times of flood discharge. The determination involved assessment of aerial photography of coastal land systems between The Murchison River and Locker Point, land system mapping, site visits and a review of available meteorologic and oceanographic information. Interpretation of the information gathered was intended to identify vulnerable locations within the Study Area and assist decision-making regarding the location of any proposed coastal development and for coastal management purposes.

Certain landforms and coastal features are more vulnerable to climate and sea level variation than others. The Zuytdorp Cliffs are a feature of the coast but indicate a general deficit of sediment in nearshore north of the Murchison River. Further north limited sediment supplies include highly irregular fluvial supply and sediment reworking of the Wooramel and Yannarie mudflats. These low-lying environments are highly susceptible to extreme metocean events; particularly river flooding resulting from high rainfall during cyclonic events and marine inundation due to storm surge and fluctuation in sea level. Bioproduction on subtidal terraces in Shark Bay and on coral reefs in Ningaloo locally contributes some sediment to inshore waters and the shore. Again these sources are markedly affected by metocean processes .and sediment may be lost to deeper water offshore.

Landform vulnerability was estimated as a combination of the susceptibility of the geological structure supporting the landforms to environmental change and the current condition of the landforms as indicated by existing evidence of erosion. Together, a geological structure and the landforms it supports define a land system. The assessment linked the integrity of the geological or geomorphologic structures of land systems and the condition or stability of the landforms supported in a matrix to estimate five grades of vulnerability (Figure A). The analysis was intended to be indicative rather than prescriptive, with applications for strategic planning purposes as a first step to more detailed risk assessment procedures.

Results included the identification of secondary coastal compartments together with an estimate of the vulnerability of each cell as shown in Table A, with boundaries shown in Figure B. Vulnerability rankings were determined on a five-point scale for each secondary compartment indicating 16 (67%) of the 24 secondary compartments had a low level of vulnerability; two (8%) were of low-to-moderate vulnerability; two (8%) were moderately vulnerable; four (16%) were of moderate-to-high vulnerability and none had a high vulnerability (Figure C). A more detailed assessment of vulnerability has been completed at a sediment cell scale for fifteen Areas of Planning Interest in the Shires of Shark Bay to Exmouth. More detail is available from the full technical report *The Gascoyne Coast, Western Australia: Shires of Shark Bay to Exmouth. Geology, Geomorphology & Vulnerability*.

			INSTABILITY (CONDITION) (Existing morphologic change to land surface)		
			Low (Stable)	Moderate	High (Unstable)
			Example		
SUSCEPTIBILITY (STRUCTURE) (Potential change to geological structure)	Low	Barrier perched on extensive tracts of coastal limestone	(1) Vegetated swales in parabolic dunes landwards of a vegetated frontal dune ridge overlying coastal limestone above HWL	(2) Vegetated dunes landwards of a vegetated frontal dune ridge and perched on coastal limestone at HWL	(3) High foredune ridge and/or vegetated foredune plain overlying coastal limestone below HWL
	Moderate	Weakly lithified barrier with intermittent limestone outcrops	(2) Mainly vegetated swales in parabolic dunes landwards of a mainly vegetated frontal dune ridge	(3) Vegetated dunes landwards of a mainly vegetated frontal dune ridge (50 to 75% cover) and overlying coastal limestone	(4) Cliffed or discontinuous foredune fronting moderate numbers of mobile blowouts and sand sheets (<50% of the alongshore reach)
	High	Barrier comprised wholly of sand. No bedrock apparent along shore or in dunes	(3) Swales in parabolic dunes landwards of a partly vegetated frontal dune ridge	(4) Mainly vegetated dunes landwards of a partly vegetated frontal dune ridge with 25 to 50% cover	(5) No foredune. Eroded frontal dune with numerous mobile blowouts and sand sheets (>50% of the alongshore reach)

KEY — **Combined estimate of vulnerability**

- Low
- Low-to-moderate
- Moderate
- Moderate-to-high
- High

Figure A: Indicative Vulnerability Matrix for a Mixed Sandy and Rocky Coast

Note: Susceptibility of a geologic structure to environmental change and the current instability of coastal landforms were estimated for each coastal cell on a three point scale as being low, moderate or high. In the matrix these were combined to provide a five point estimation of the vulnerability.

Table A: Susceptibility, Instability and Vulnerability Rankings for Each Secondary Compartment

Secondary Compartment	Susceptibility Rank	Instability Rank	Vulnerability Rank
Giralia to Locker Point	M	M	M
Learmonth to Giralia	L	L	L
North West Cape to Learmonth	L	L	L
Winderabandi Point to North West Cape	L	L	L
Point Cloates to Winderabandi Point	H	M	M-H
Point Maud to Point Cloates	L	L	L
Alison Point to Point Maud	L	L	L
Gnaraloo Bay to Alison Point	L	L	L
Cape Cuvier to Gnaraloo Bay	L	L	L
Point Quobba to Cape Cuvier	M	L	L-M
South Bejaling Hill to Point Quobba	M	H	M-H
Grey Point to South Bejaling Hill	H	M	M-H
Wooramel coast to Grey Point	L	M	L-M
Nilemah coast E to Wooramel coast	L	L	L
Petit Point to Nilemah coast E	L	L	L
Monkey Mia to Petit Point	L	L	L
Cape Peron North to Monkey Mia	L	L	L
Goulet Bluff to Cape Peron North	L	L	L
Giraud Point to Goulet Bluff	L	L	L
Cape Bellefin to Giraud Point	L	L	L
Cape Inscription to Cape Bellefin	M	M	M
Steep Point to Cape Inscription	L	L	L
Nunginjay Spring coast N to Steep Point	L	L	L
Murchison River to Nunginjay Spring coast N	M	H	M-H

Key	Vulnerability of environmental change	Implications for coastal management (see Table 2-11 in the full report for further description)
(green)	Low	Coastal risk is unlikely to be a constraint to coastal management
(light green)	Low -to-moderate	Coastal risk may present a low constraint to coastal management
(yellow)	Moderate	Coastal risk may present a moderate constraint to coastal management
(peach)	Moderate-to-high	Coastal risk is likely to be a significant constraint to coastal management
(red)	High	Coastal risk is a highly significant constraint to coastal management

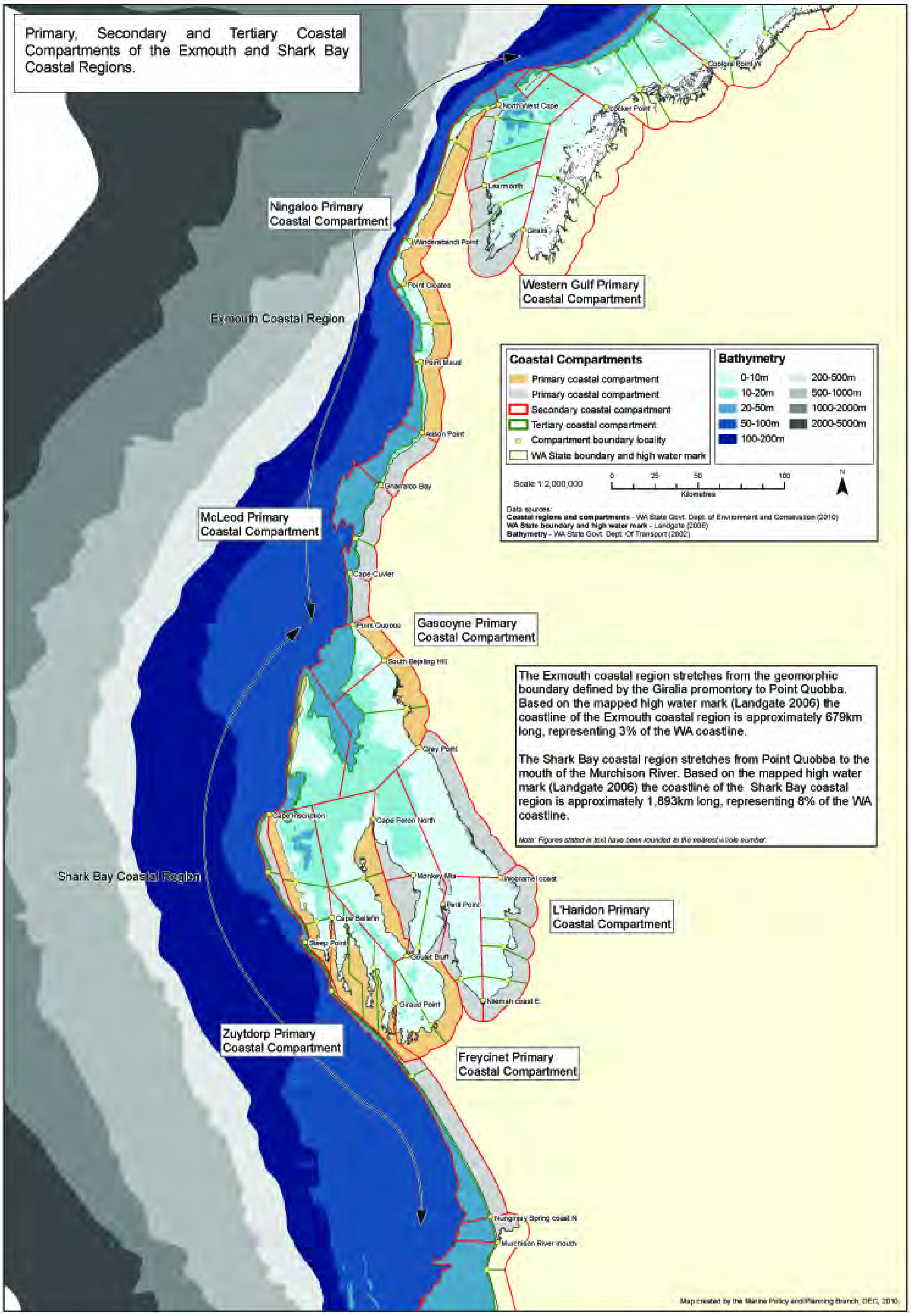

Figure B: Study Area and Secondary Compartment Boundaries for the Gascoyne Coast

Note: Compartments were defined as large sections of coast with a common land system. Three levels were identified from primary to tertiary compartments, with the offshore boundaries at the 130m, 50m and 20m depth contours. Each compartment contained a number of sediment cells to which the vulnerability rankings were ascribed. The vulnerability rankings referred to the cell as a whole but not to individual landforms. Different landforms within each cell were likely to have higher or lower levels of vulnerability than the cell as a whole.

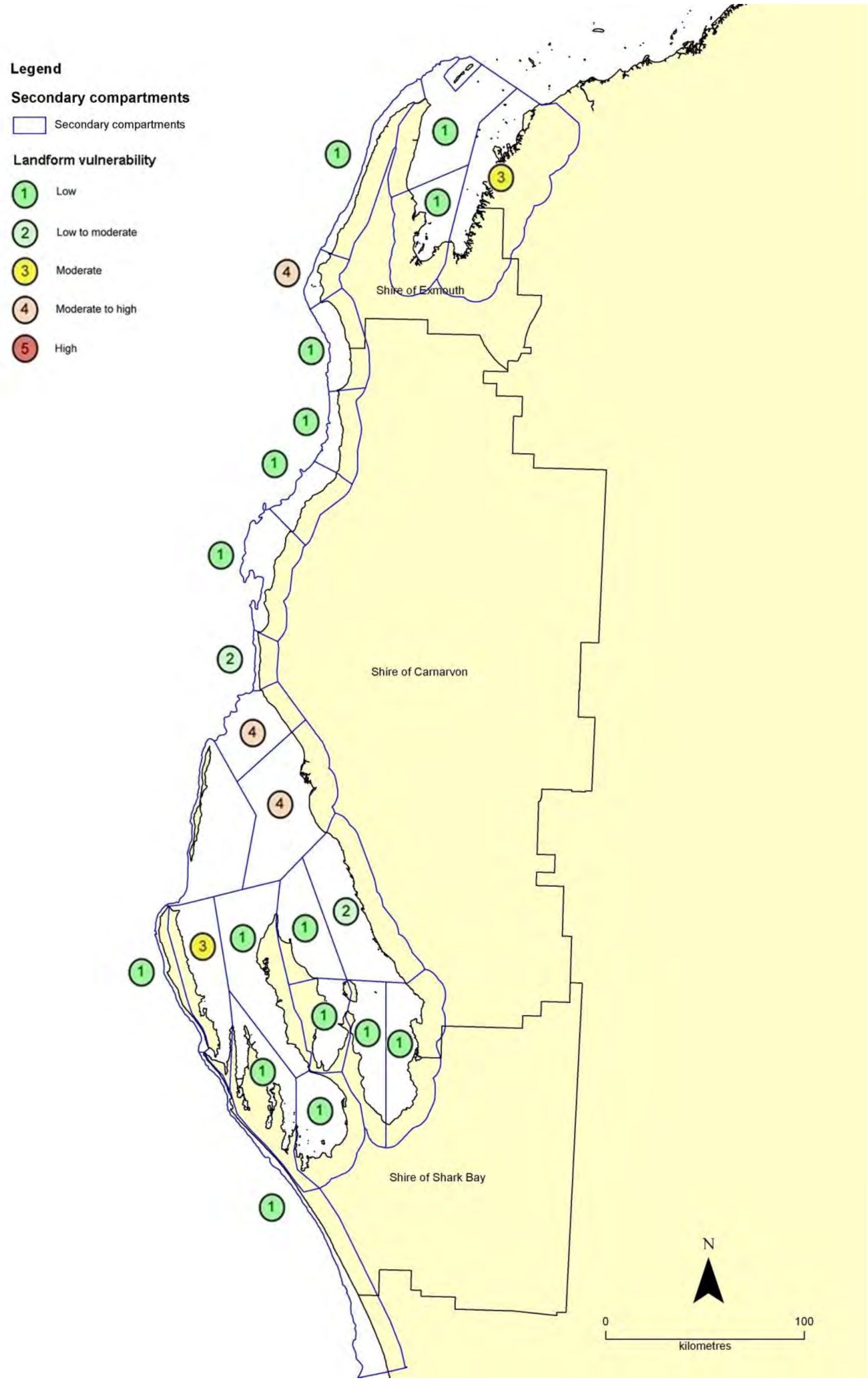

Figure C: Vulnerability Rankings of Secondary Compartments of the Gascoyne Coast

Note: Compartment labels are contained within the report

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1. Introduction

This document provides information regarding coastal landform vulnerability along the Gascoyne coast, to support strategic planning and facilitate more detailed local-scale risk assessments. The project, through collaboration with Geological Survey of Western Australia, identifies land systems and the landforms they contain along the Gascoyne coast between the mouth of the Murchison River near Kalbarri and Locker Point on the eastern shore of Exmouth Gulf (Figure 1-1). Coastal vulnerability has been assessed by identifying landforms that are likely to alter in response to changes in meteorologic and oceanographic processes. Changes of interest are those occurring over two time scales: observable landform changes presently taking place over sub-decadal time scales; and those projected to occur over a planning horizon of 100 years.

The vulnerability analysis has been conducted at a coastal compartment scale with selected areas at a sediment cell scale, and therefore is indicative rather than prescriptive at the scale of landform elements (infrastructure or engineering scales). Additional information is required to develop coastal hazard mitigation strategies. Further investigations will be required to identify and assess the magnitude and timing of specific risks to existing and planned use of the coast as well as to develop strategies and detailed plans for risk management and mitigation.

For known Areas of Planning Interest, local scale results of the coastal vulnerability analysis have been considered in the context of available planning documents. Coastal planning information has been considered with respect to the general objectives of the *Coastal Zone Policy for Western Australia* (Western Australian Planning Commission: WAPC 2001) and the more specific guidance provided by Statements of Planning Policy (WAPC 2003, 2006). For the purpose of advice contained in this assessment, these coastal planning criteria have been used as a benchmark with which to identify coastal management constraints. This approach simplifies the planning process, and hence all study recommendations should be recognised as advice, rather than requirements.

1.1. AIMS AND OBJECTIVES

Nationally, Western Australia boasts an enviable diversity of coastal landforms. The diversity includes areas of outstanding beauty such as the World Heritage Area at Shark Bay (Department of Environment and Conservation: DEC 2008) as well as low lying areas in the Pilbara (Semeniuk 1996a) and estuaries of the south west coast (Brearley & Hodgkin 2005) that are prone to inundation by flooding and storm surge (Department of Climate Change: DCC 2009). This has been acknowledged through formulation and adoption of the *Coastal Zone Management Policy for Western Australia* (WAPC 2001) and the *Western Australian Coastal Management Plan* (WAPC 2002). The *Coastal Zone Management Policy* provides objectives for management of the coastal zone and the multiple uses it supports, with the *Coastal Management Plan* providing direction for where the policy should be applied. Operating under this policy and plan are the State Coastal Planning Policy SPP No. 2.6 (WAPC 2003) that provides advice on calculating coastal setbacks and the Coastal Protection Policy (DPI 2006) which provides a framework for allocation of funding for erosion mitigation works through the Coastal Protection Funding Program. The policies are founded on long-standing governance of the coast by State and Local Government authorities and the well-founded interest and commitment of coastal communities.

Coastal management in Western Australia has long recognised the dynamic nature of coastal environments and its consequences for coastal development and land use. Coastal planning and management policies have been intended to mitigate existing and anticipated management problems in areas subject of coastal hazards through intelligent siting and design of infrastructure based on ongoing scientific research (WAPC 2001). Generally, the policies have provided space for natural coastal change to occur as well as facilitating conservation and recreation in many places around the State. Prior to their formulation, lack of focussed policy or subsequent poor application resulted in considerable cost to Local and State Government through the establishment of land uses dependent on recurrent maintenance or frequent replacement of amenities. The historical shortcoming devolved on-going management and maintenance responsibility to current and future generations. Long standing coastal management problems at Augusta, Busselton, Cottesloe, Cervantes, and Geraldton provide examples of historical management problems that persist today. More catastrophic problems have been experienced with severe flooding and the impacts of tropical cyclones in the Pilbara and Kimberley, as has been demonstrated by repeated destruction and relocation of townsite and jetty facilities at Onslow. Since adoption of coastal planning policies in the early 1970's, preparation of coastal plans, consultancy projects and local research has substantively added to our knowledge of coastal landforms and the processes shaping them. The policies essentially apply McHargian principles (McHarg 1995) to plan land use in the context of the natural environment. The investigations underlying them are now sufficiently detailed to assist mitigation of projected future problems. Hence, an aim of this report has been to review the available information and use it to assess potential land system and landform change over a planning horizon of up to 100 years.

Examination of the coastal geomorphology between Murchison River to Locker Point involved assessment of aerial photography of the study area, site visits and a review of relevant and available metocean information. It was conducted at two spatial scales:

- First land systems and major landform components comprising discrete coastal compartments of the Study Area (Figure 1-2) were identified and described. *Coastal compartments* are natural structural features. They are primarily related to the regional geologic framework of the coast which exerts structural control on the plan form of unconsolidated coastline. The compartments are secondarily dependent on coastal aspect, land systems, and large coastal landforms such as deltas and cuspate forelands visible at a scale of 1:100,000 to 1:250,000. They are comprised of large scale geologic and geomorphologic features subject to significant changes over decades to millennia.
- Second, *sediment cells* in 15 nominated areas of planning interest were examined in more detail. Sediment cells commonly are smaller three-dimensional units (Figure 1-3 to Figure 1-5) nested within the broader compartments. In the context of this report they are identifiable at scales of 1:10,000 to 1:25,000 or larger at a more detailed local level. The cells are functionally defined by the likely movement of unconsolidated sediments between source areas and sinks via transport pathways within geologic and

geomorphic boundaries. Landforms comprising the cells are likely to change in response to sub-decadal, including seasonal and higher frequency changes in metocean processes. In part the distinction between compartments and cells also is based on the potential ease of determining a sediment budget from available information. Some tertiary compartments are large sediment cells.

Sediment cell and sediment budget concepts have been described in more detail by Davies (1974), Chapman *et al*. (1982), Dolan *et al*. (1987), Komar (1996), van Rijn (1998), Short (1999), Rosati (2005) and Whitehouse *et al*. (2009a).

Within the compartments and cells some land systems and landforms are more susceptible to long-term variation in climate and sea level than others. Additionally the current condition of landforms, either comprising the system or as individual units varies from place to place. For example, a large barrier system with a wide and high dune field may be less susceptible to change in the natural structure than a narrow barrier with low dunes. However, dunefields on similarly-located high, wide barrier structures may have dunes that are currently stable and well vegetated or dunes that are highly unstable with mobile sand sheets present. Hence a distinction is made between land system or landform susceptibility and instability.

Some direction concerning projected future change to the coastal environment was provided by the Department of Climate Change (2009: 41). The agency noted that an expected impact of projected climate change will be accelerated coastal erosion due to rising sea levels. However this concept is necessarily dependent on the availability of unconsolidated sediment to accommodate short-term instability of landforms without a tipping point being reached which changes the geological structure supporting them. The response of the coast to projected change is complex due to the space and time scales at which different metocean conditions, local lithology and sediment factors affecting the morphology operate, including the following:

1. Local topographic factors, including the geologic framework supporting the coast;
2. The inherent susceptibility of different unconsolidated sedimentary landforms due to their structure and composition;
3. Coastal sediment budgets, including geomorphic features that act as sediment sinks or sources; and
4. Natural geographic variability in the metocean processes, particularly changes in sea level and the wave regime, affecting the stability of landform in the area of interest.

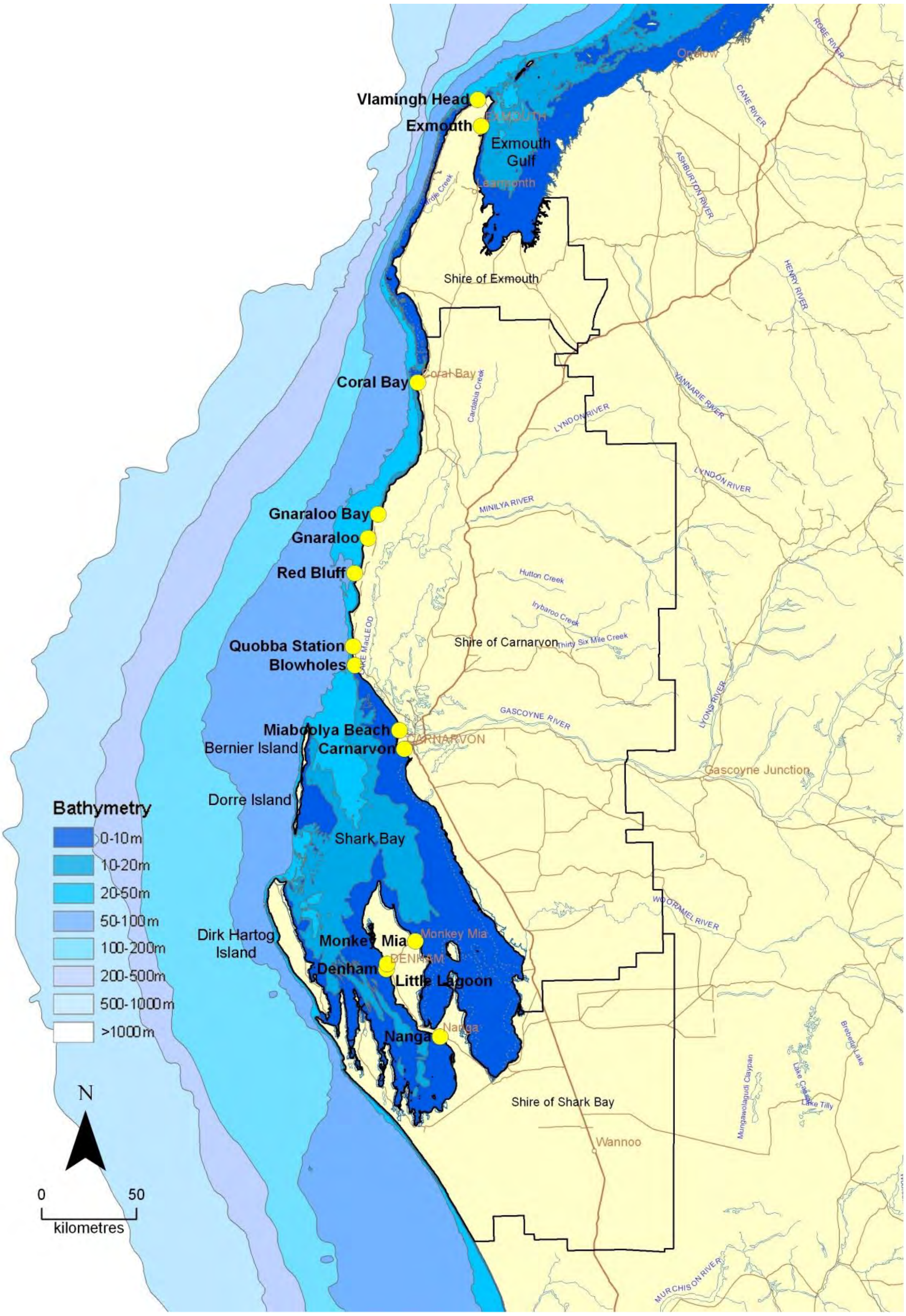


Figure 1-1: Study Area

The Study Area extends from Murchison River to Locker Point

Yellow dots identify Areas of Planning Interest for more detailed examination

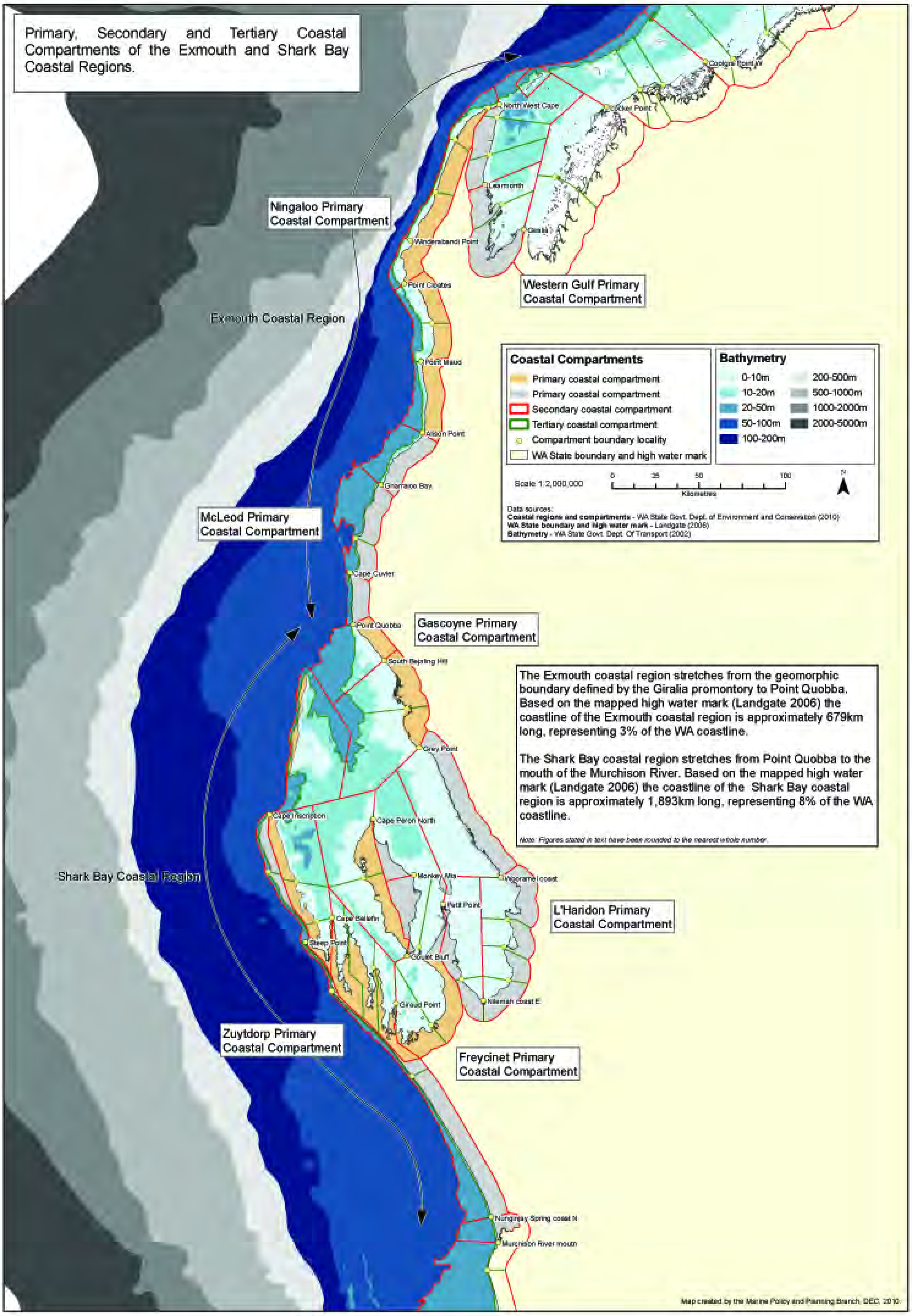


Figure 1-2: Gascoyne Coastal Compartments
(Source: Eliot *et al.* 2011)

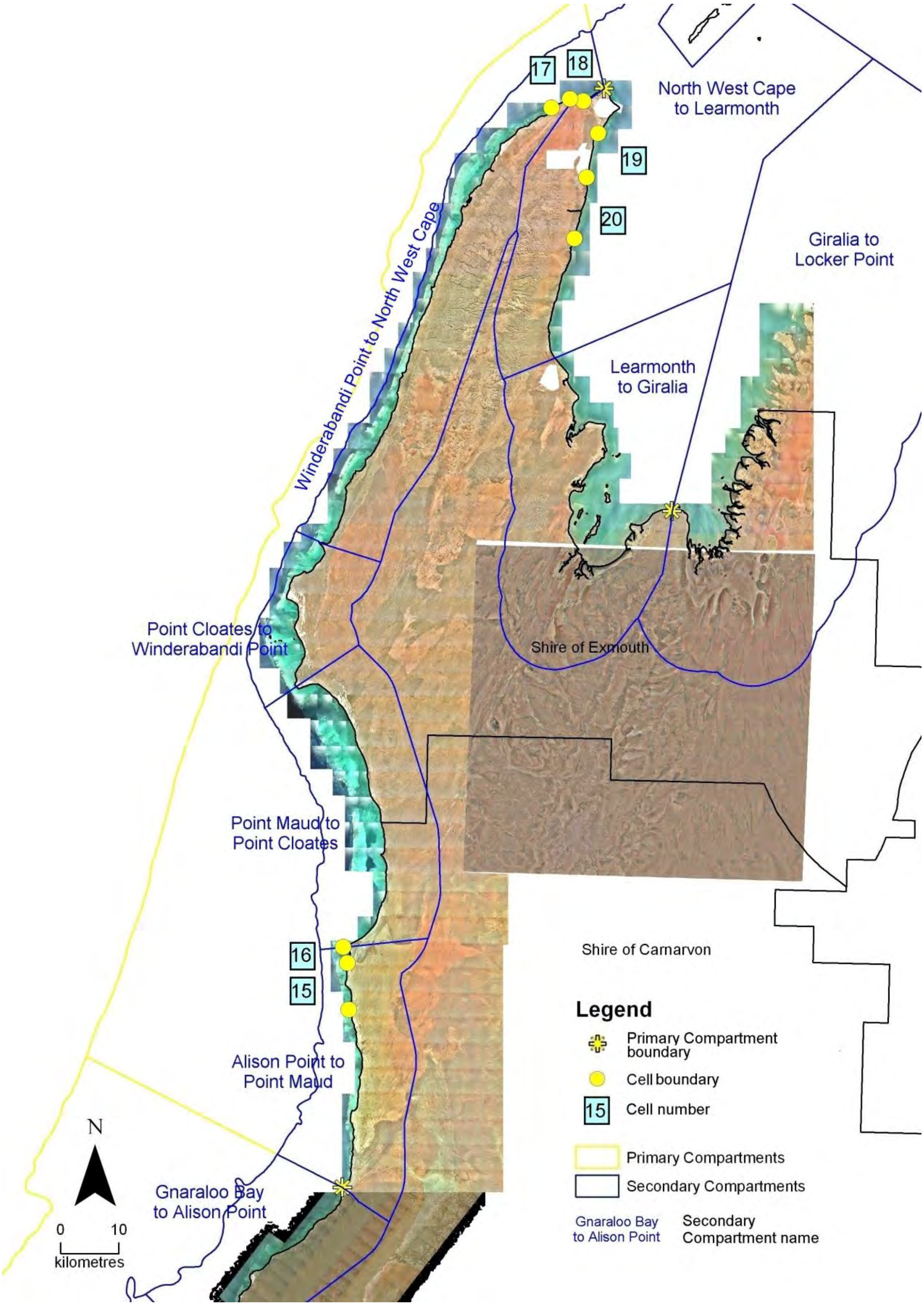


Figure 1-3: Compartments and Sediment Cells (15-20)
Offshore boundaries are at the 130m and 50m bathymetric contour for primary and secondary compartments (Table 2-4) and correspond with significant geologic features and metocean conditions (Eliot *et al.* 2011).

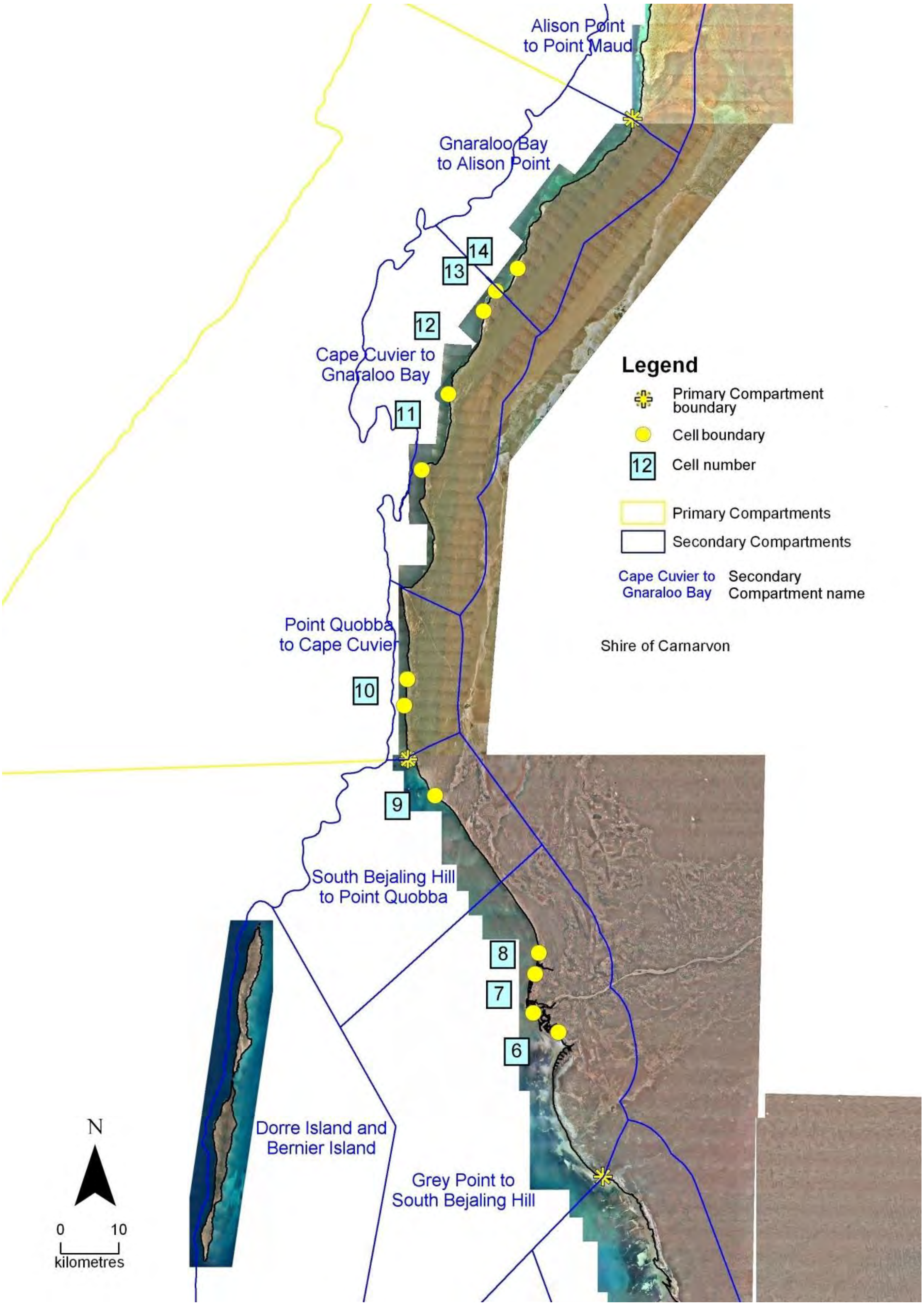


Figure 1-4: Compartments and Sediment Cells (6-14)
Offshore boundaries are at the 130m and 50m bathymetric contour for primary and secondary compartments (Table 2-4) and correspond with significant geologic features and metocean conditions (Eliot *et al.* 2011).

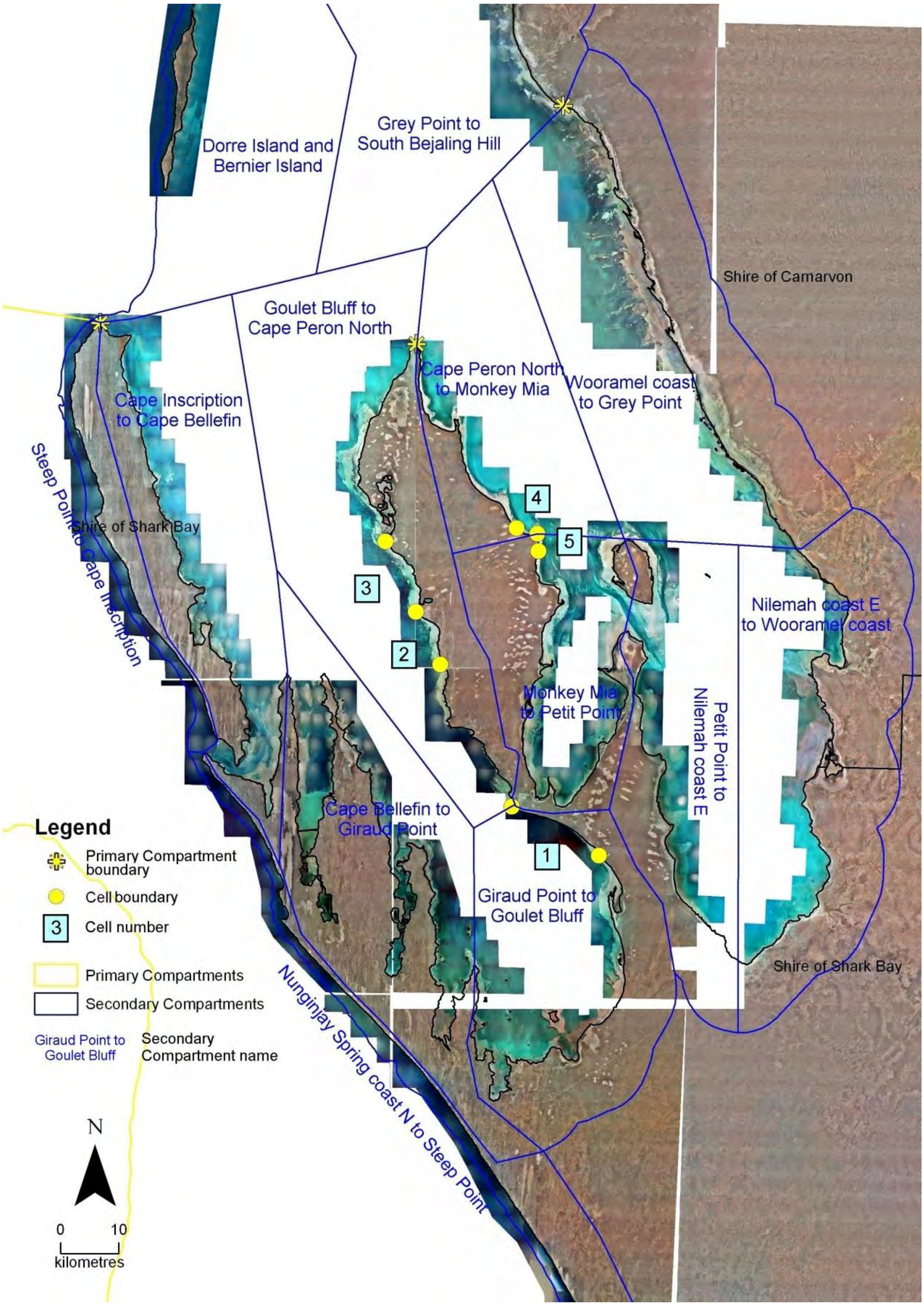


Figure 1-5: Compartments and Sediment Cells (1-5)
Offshore boundaries are at the 130m and 50m bathymetric contour for primary and secondary compartments (Table 2-4) and correspond with significant geologic features and metocean conditions (Eliot *et al.* 2011).

The objectives of the project are to describe the geomorphology of the coast of the Shires of Shark Bay, Carnarvon and Exmouth in Western Australia (Figure 1-1) at a broad, strategic planning scale. Description of the land systems and landforms comprising the coast is used to provide an indication of potential coastal responses to projected change in metocean forcing. In turn the information presented is intended to identify the nature and degree of investigation required to support management proposals for the land system or landform under consideration.

It was intended these objectives would be met by:

1. First–pass identification and description of coastal landforms, with particular reference to coastal dunes, beaches, rocky shores and inshore morphology.
2. Broad-scale identification of landforms and reaches of coastal land susceptible to risks related to natural variation in climate and sea level fluctuations, and which may be affected by projected changes in climate.

The outcomes are anticipated to contribute to strategic planning for the Study Area as well as to add detail to State and National databases particularly the Oil Spill Response Atlas: OSRA (AMSA 2006), Smartline (Sharples *et al.* 2009) and WACoast (Gozzard 2012) databases for the coastal area being examined.

1.2. TASKS

A key task in the examination of coastal land systems for strategic coastal planning in the Shires of Shark Bay to Exmouth was to provide an indicative assessment of coastal vulnerability to changing metocean processes that is consistently applicable at all planning scales, which guides potential land use and potentially has relevance to upscaled or downscaled responses to risk aversion or mitigation. This task builds on the approach developed for the Shires of Gingin to Northampton (Eliot *et al*. 2012a, b) for assessing coastal vulnerability to changing metocean processes.

The following steps were completed in order to accomplish this task and fulfil the objectives of the project:

1. Identify natural resource management units at scales commensurate with regional and local planning scales recommended by the WAPC (2003);
2. Describe the geology and Holocene landforms, particularly those developed over the past 6,000 years, comprising each planning unit;
3. Through comparison of the physical features in each planning unit, determine areas of coastal land likely to require different planning and management approaches;
4. Develop a framework for assessment of coastal vulnerability that is consistently applicable at all planning scales; and
5. Apply the framework at broad scale strategic and local planning scales through its application to tertiary coastal compartments and large sediment cells.

1.3. APPROACH

In this report the approach used is a hierarchical land system analysis focussing specifically on description of a framework provided by the geology and geomorphology of the coast. It has similarities to the hierarchical classification used for mapping of soils in WA (Schoknecht *et al.* 2004; van Gool *et al.* 2005). Land system analysis is used because it:

> *'… provides a framework by which appropriately formulated policies can be linked to distinctive components of the landscape (hierarchically arranged as land systems and constituent land units) and their various features and management needs.'* (Hames Sharley Australia 1988: 12)

The approach used here has been adapted to coastal planning purposes similar to those applied by Whitehouse *et al.* (2009a) in the characterisation and prediction of large scale, long-term change of coastal geomorphological behaviour around the coast of the United Kingdom. A similar approach has been applied to Coffs Harbour in NSW by Rollason *et al.* (2010) and Rollason & Haines (2011). Rollason *et al.* (2010) noted that the Draft *Guidelines for preparing Coastal Zone Management Plans* (Department of Environment, Climate Change and Water NSW 2010)

> *'separate the coastline into its broad geomorphologic sub-groups, being either sandy beach systems, bluffs and cliffs comprising rock and other consolidated material, or the entrance area of estuaries/watercourses at the coast.'*

They established methods for application of the *AS/NZS ISO 31000:2009 Risk Management Principles and Guidelines* (Standards Australia 2009) to coastal management. In their methodology it is important to set the context for which a land system or all of the geomorphologic components a risk assessment and management plan is intended to address. Description of the context is the first phase of the risk assessment process and accords with the coastal processes and hazards definition phase of the traditional coastal planning process (Rollason *et al.* 2010).

The projected changes of interest are those spanning two time and space scales; short (sub-decadal) and long (over a planning horizon of 100 years) term changes occurring at secondary compartmental (approximately 1:100,000) and primary sediment cell (approximately 1:25,000) scales. This necessarily requires examination of changes at land system (landform pattern) and landform levels in the land system hierarchy, with the broader scales providing context for more detailed interpretation and morphologic changes at the more detailed scales potentially providing explanation for long-term change.
The land system approach adopted has three significant features:

1. The scalar hierarchy is commensurate with regional and local planning scales recommended by the WAPC (2003);
2. It has been applied to coastal or marine management elsewhere in Australia (NSW Government 1990; Government of South Australia 2006; Rollason & Haines 2011) and overseas (Kelley *et al.* 1989; Hart & Bryan 2008; and Whitehouse *et al.* 2009a, b); and
3. A method of analysis can be developed for consistent application at all levels in the hierarchy.

The methods used facilitated assessment of a combination of coastal susceptibility to projected environmental change and current landform stability. As indicated above the combination described in this report is based on the identification of secondary coastal compartments and large sediment cells. The former is intended for strategic regional planning and policy development, and the latter for local area planning. Coastal vulnerability for each compartment or cell is estimated as a function of the susceptibility of the geologic structure or land system of the coast to changing metocean regime and the present condition or stability of each landform the land system supports. The estimated vulnerability provides an indication of the management pressures likely to accord for land-use within each whole compartment or cell relative to others in a series described for a region or administrative coastal area. The methods used to evaluate coastal susceptibility, stability and vulnerability are outlined in Section 2.

1.4. DOCUMENT USE

A methodology to assess coastal vulnerability to changes in climate and sea level has been applied at compartmental and sediment cell scales, which respectively correspond to map scales of approximately 1:100,000 and 1:25,000 for strategic and local planning purposes. An overall estimate of vulnerability has been made for each secondary compartment and for sediment cell in areas of planning interest. The overall vulnerability is intended to provide an indication of the management pressures likely to accord for land-use within the compartment or cell as a whole as well as to facilitate comparison between different sectors of coast.

As a consequence, the estimates of vulnerability do not provide an adequately objective measure of stability for specific land-uses that may be active within a limited portion of compartments or cells or uses which operate over multiple adjacent cells. It should be clearly recognised that landform classification provides only a basic, qualitative measure of potential for change, and hence the information should be used with caution. Equally, the higher resolution landform mapping presented offers further spatial refinement, but the stability of individual landforms within such classes is quite variable. Hence, this report provides direction regarding the suitability of coastal land for specific uses, but further detailed risk assessment at a local, site scale may be necessary.

2. Methods

Coastal vulnerability was estimated as follows:

1. Separate planning units were identified at a scale appropriate to strategic and local area planning;
2. Land systems and landforms were identified and mapped for each planning unit; respectively at a secondary compartment or a sediment cell scale;
3. Ranking scales for susceptibility and instability were derived from published conceptual models respectively describing sequences of coastal development or different degrees of coastal instability.
4. The major natural structural features of planning units were described and ranked according to their likely susceptibility to change;
5. Landforms within each compartment or cell were described and ranked according to their present stability and an overall ranking of instability ascertained;
6. The overall susceptibility and instability rankings were separately grouped into low, moderate and high categories for each planning unit; and
7. The vulnerability of each compartment or cell was estimated by combining the overall rankings of susceptibility and instability in a matrix to identify the likelihood of geomorphic change, grouped into low, low-to-moderate, moderate, moderate-to-high and high categories.

Consequences for the resulting vulnerability estimates were then interpreted for each planning unit and form the basis of recommendations made in the report. These steps are outlined below.

2.1. IDENTIFICATION OF PLANNING UNITS

The hierarchy of compartments and sediment cells comprise two sets of planning units, secondary compartments and sediment cells (Table 2-1; Figure 1-3 to Figure 1-5). In the context of this report they are areas sharing physical features apparent at mapping scales respectively appropriate to regional and local planning. At each scale the approach used focused on description of the structural framework provided by the geology, and to a lesser extent, large geomorphic features formed of unconsolidated sandy sediment.

Four sets of features were used to identify the alongshore boundaries of coastal compartments. These are listed in Table 2-2 and examples of boundaries are provided in Figure 2-1. The offshore boundaries of the compartments and cells as well as their interpretation in terrestrial coastal planning are outlined in Table 2-3. Onshore, the boundary of the compartments and cells is either the landward extent of marine and eolian sediments deposited over the past 10,000 years, during the Holocene, as the present coast developed; or approximately 500 metres landward from the rocky shoreline. At each scale, landforms and the processes affecting them (Table 2-4) provide an approach to interpretation and implementation of the State Coastal Planning Policy SPP No. 2.6 (WAPC 2003) and/or the Coastal Protection Policy (DPI 2006).

Overall, the approach is multi-scalar and the methodology applicable at both scales used in the report. It ranges from broad-scale strategic consideration of the secondary compartments along the Gascoyne Coast to more detailed identification of areas nominated as requiring special consideration for planning purposes. At each scale this is done through facilitation of a qualitative ranking of landforms to risk of change based on separate estimates of geologic and geomorphic features to potential change in combination with the current condition or instability of the land surface. These are then combined to provide a ranked estimate of vulnerability.

Table 2-1: Compartments and Sediment Cells

Note: + primary cell considered; ++ secondary cell considered

Compartment			Cell
Primary	**Secondary**	**Tertiary**	**Primary**
EASTERN GULF: Giralia to Locker Point	Giralia to Locker Point	Hope Point to Locker Point	
		Giralia to Hope Point	
WESTERN GULF: North West Cape to Giralia	Learmonth to Giralia	Point Lefroy to Giralia	
		Learmonth to Point Lefroy	
	North West Cape to Learmonth	Shothole Canyon North to Learmonth	
		Bundegi to Shothole Canyon North	Qualing Pool to Shothole Canyon North
			20. Exmouth North to Qualing Pool +
			19. Bundegi to Exmouth North +
		North West Cape to Bundegi	
NINGALOO: Alison Point to North West Cape	Winderabandi Point to North West Cape	Vlamingh Head to North West Cape	18. Secondary cell is Vlamingh Head to East Vlamingh ++ (Primary cell is Vlamingh Head to North West Cape)
		Low Point to Vlamingh Head	17. Secondary cell is Babjarrimannos to Vlamingh Head ++ (Primary cell is Vlamingh South to Vlamingh Head)
			Note. Further cells not delineated
		Osprey Bay to Low Point	
		Winderabandi Point to Osprey Bay	
	Point Cloates to Winderabandi Point	Point Cloates to Winderabandi Point	
	Point Maud to Point Cloates	Coast Hill to Point Cloates	
		Point Maud to Coast Hill	
	Alison Point to Point Maud	Alison Point to Point Maud	16. Purdy Point to Point Maud +
			15. Point Anderson to Purdy Point +
			Pelican Point to Point Anderson
			Alison Point to Pelican Point
MACLEOD: Point Quobba to Alison Point	Gnaraloo Bay to Alison Point	Gnaraloo Bay to Alison Point	Note. Further cells not delineated
			14. Gnaraloo Bay South to Gnaraloo Bay North +
	Cape Cuvier to Gnaraloo Bay	Red Bluff to Gnaraloo Bay	13. Gnaraloo North to Gnaraloo Bay South
			12. Gnaraloo South to Gnaraloo North +
			11. Red Bluff to Gnaraloo South +
		Cape Cuvier to Red Bluff	
	Point Quobba to Cape Cuvier	Point Quobba to Cape Cuvier	Note. Further cells not delineated
			10. Secondary cell is Quobba Station South to Quobba Station North +
			Note. Further cells not delineated

Compartment			Cell
Primary	**Secondary**	**Tertiary**	**Primary**
GASCOYNE: Grey Point to Point Quobba	South Bejaling Hill to Point Quobba	South Bejaling Hill to Point Quobba	9. Fitzroy Reefs to Point Quobba +
			Bejaling Hill to Fitzroy Reefs
			South Bejaling Hill to Bejaling Hill
	Grey Point to South Bejaling Hill	West Side Creek to South Bejaling Hill	Miaboolya Beach to South Bejaling Hill
			8. Gascoyne River North to Miaboolya Beach +
			7. Gascoyne River South to Gascoyne River North +
			6. Massey Bay to Gascoyne River South +
			West Side Creek to Massey Bay
		Grey Point to West Side Creek	
L'HARIDON: Cape Peron North to Grey Point	Wooramel coast to Grey Point	Wooramel coast to Grey Point	
	Nilemah coast E to Wooramel coast	Hamelin Pool to Wooramel coast	
		Yaringa Point to Hamelin Pool	
		Goat Point to Yarringa Point	
		Nilemah coast E to Goat Point	
	Petit Point to Nilemah coast E	Booldah well to Nilemah coast E	
		Petit Point to Booldah well	
	Monkey Mia to Petit Point	Taillefer Spit to Petit Point	
		Monkey Mia to Taillefer Spit	Note. Further cells not delineated
			5. Secondary cell is Monkey Mia to Eastern Bluff ++ (Primary is Monkey Mia to Dubaut Point)
	Cape Peron North to Monkey Mia	Cape Peron North to Monkey Mia	4. Secondary cell is Red Cliff Bay to Monkey Mia ++ (Primary s Cape Rose to Monkey Mia)
			Guichenault Point to Cape Rose
			Cape Peron North to Guichenault Point
FREYCINET: Cape Inscription to Cape Peron North	Goulet Bluff to Cape Peron North	Middle Bluff to Cape Peron North	
		Goulet Bluff to Middle Bluff	3. Lagoon Point to Middle Bluff +
			2. Denham South to Lagoon Point +
			Eagle Bluff to Denham South
			Goulet Bluff to Eagle Bluff
	Giraud Point to Goulet Bluff	Fording Point to Goulet Bluff	1. Nanga Bay to Goulet Bluff +
			Fording Point to Nanga Bay
		Giraud Point to Fording Point	
	Cape Bellefin to Giraud Point	Cararang Peninsular North Point to Giraud Point	
		Cape Heirisson to Cararang Peninsular North Point	
		Cape Bellefin to Cape Heirisson	
	Cape Inscription to Cape Bellefin	Tumbledown Point to Cape Bellefin	
		Herald Bay North to Tumbledown Point	
		Cape Inscription to Herald Bay North	

Compartment			Cell
Primary	Secondary	Tertiary	Primary
ZUYTDORP: Murchison River to Cape Inscription	Steep Point to Cape Inscription	Quoin Head to Cape Inscription	
		Steep Point to Quoin Head	
	Nunginjay Spring coast N to Steep Point	Zuytdorp Point to Steep Point	
		Kakura Dunes coast to Zuytdorp Point	
		Nunginjay Spring coast N to Kakura Dunes coast	
	Murchison River to Nunginjay Spring coast N	Murchison River to Nunginjay Spring coast N	

Table 2-2: Features Used to Establish the Boundaries of Each Coastal Compartment

Priority	Feature	Examples
1	Changes in geology	Metamorphic to sedimentary rocks; lithified to unconsolidated sediments
2	Rock structures (topography)	Rocky capes, peninsulas, termination of extensive cliffs
3	Geomorphic features (morphology)	Large cuspate forelands and tombolos; extensive sandy beaches
4	Change in aspect of the shore	Bald Head at the entrance to King George Sound; changes in aspect along Eighty Mile Beach

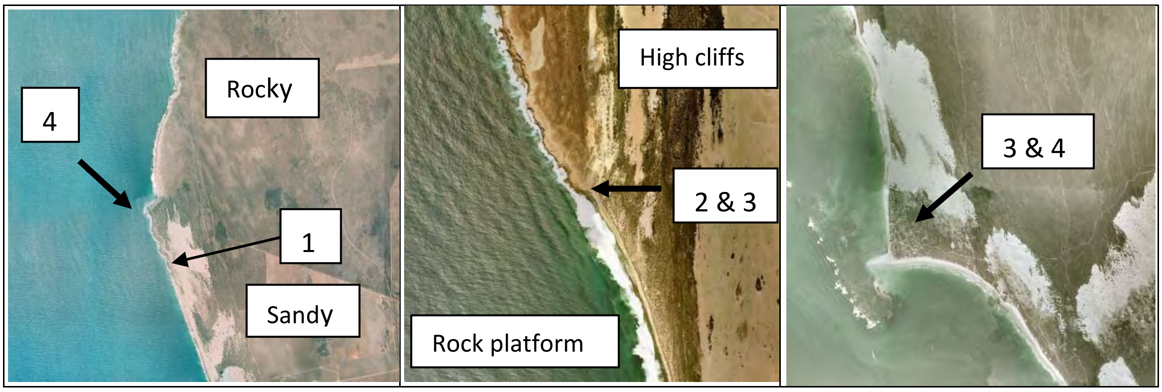


Figure 2-1: Examples of Compartment Boundaries

1 = change in geology; 2 = rock structure; 3 = geomorphic feature; and 4 = change in aspect

= Primary boundary **= Secondary boundary**

Table 2-3: Offshore Boundaries of Coastal Compartments and Cells, and their Potential Management Application

Boundary (isobath)	Land System/Landform Scale and Geology	Management Application
Primary Compartments (130 metres)	Mega-scale land systems e.g. Barriers, river deltas, zeta-form beaches Geological development of the coastal plan form occurs at this scale. Marine processes affecting the inner continental shelf establish the geological setting of coastal land and its broad susceptibility to long-term erosive forces operating over decades, centuries and millennia.	The inner continental shelf is significant for marine resource planning and management because it supports a high proportion of aquatic biota fished for commercial and recreational purposes, and which demand land based infrastructure for its exploitation. Primary compartments are areas of substantial overlap between Commonwealth and State interests. Waters beyond State Water boundary at 3nm (approximately 6km) are jointly managed through an intergovernmental agreement.
Secondary Compartments (50 metres)	Meso- to Macro-scale land systems and landforms e.g. Cuspate forelands, tombolos and dune sequences Holocene, including present day, development of the coastal plan form occurs at this scale. The topographic structure of the inner continental shelf affects wave patterns and nearshore water circulation. Coastal changes are apparent at interannual to decadal time periods.	Closer to shore, this is the area of most intense use of the marine environment for commercial and recreational purposes, including recreation and tourism. Meso-scale landforms are apparent as components of coastal sediment cells and sediment budgets at this scale. They identify areas of relative coastal stability as well as susceptibility to change, and hence indicate potential problems for coastal planning and management. In this context there may be a requirement for detailed studies at a local scale.
Tertiary Compartments (20 metres)	Micro- to Meso- scale landforms. e.g. beaches, foredunes and blowouts. Inshore topography landward of the 20m isobath determines the nearshore wave regime and current patterns that drive the coastal sediment budget. It has a direct effect on the stability of coastal landforms, particularly those comprised of unconsolidated sediment. Coastal changes are apparent at seasonal and interannual to decadal scales.	The inshore waters and coastal lands are critical for provision and maintenance of marine based infrastructure (harbours and marinas). In addition to its commercial value, the area comprises a substantial proportion of State Waters and is highly significant for coastal recreation. Landforms within the tertiary components are directly related to sediment cells. They include indication of areas likely to be unstable and which may require special consideration for coastal management at a local level.
Sediment Cell (Offshore boundary linked to local sediment movement)	Micro- to meso-scale landforms associated with areas of active sediment production, mobilisation, transport and deposition. e.g. seagrass beds, scour channels, longshore troughs, beaches and mobile dunes. Micro- to meso-scale landforms comprise the major components of the coastal sediment budget and are directly related to coastal stability. Landform change may be apparent at hourly to seasonal scales.	The active components of the coast are considered under Section C of the State Coastal Planning Policy (SPP No. 2.6) in the calculation of requirements for the set back of development from the active beach. They are identified through changes in the beach profile, the position of the shoreline and migration of active dunes.

Table 2-4: Application of Coastal Compartments & Sediment Cells at Planning Scales

COMPARTMENT		DESCRIPTORS			
PLAN (Compartment)	**OFFSHORE LIMIT (Depth Contour)**	**GEOLOGY & GEOMORPHOLOGY**	**Meteorologic**	**KEY PROCESSES Oceanographic**	**Landform Change**
POLICY (State or Region)	Continental shelf boundary (250m isobath)	Broad scale geology & coastal land systems	Climate zone & global weather scales such as the Walker Circulation & Southern Oscillation	Broad-scale tidal environment; Deepwater wave environment; Geographic variation in major ocean currents	Main natural structural features & landscapes; Broad-scale (geologic) evolution of the coast
STRATEGIC PLAN (Primary Compartment)	Interglacial low sea level (130m isobath)	Shoreface geological structures & coastal land systems and form patterns (eg. Episodic transgressive sand barrier)	Distribution of major weather systems affecting the region, including those associated with extreme events	Broad-scale tidal regime; Inter-annual and long-term variation in mean sea level; Deepwater wave environment; Outer shelf current regime	Geological development of major land systems apparent at a regional scale (eg. barrier type)
REGIONAL PLAN (Secondary Compartment)	Present day shoreface (50m isobath)	Sub-regional geologic framework & large geomorphic responses (eg. Nested blowouts overlying long-walled parabolic dunes)	Major weather systems & assessment of regional scale risks associated with their onset & passage	Water level characteristics & range (tide & surge); Seasonal to inter-decadal fluctuation in mean sea level; Inner-shelf wave & current regime	Landform patterns (eg. nested dunes on a barrier); Broad changes occurring to coastal landforms at seasonal, inter-annual and inter-decadal time scales
LOCAL or SITE PLAN (Tertiary Compartment)	Inshore sediment movement (Offshore 20m isobath)	Local geologic framework, geomorphologic structures & individual landforms (eg. Mobile sand sheet and active parabolic dune)	Regional & local weather systems together with local or site scale assessment of risks associated with their onset & passage	Water level regime at site level; Seasonal and inter-annual fluctuation in mean sea level; Nearshore wave & current regimes	Landforms and landform elements; Description of shoreline movement and landform change at sub-decadal intervals; Local dynamics in response to metocean processes
LOCAL or SITE PLAN (Sediment Cell)	Depends on the size of the cell and location of offshore sediment sinks, hence overlap with planning scales	Areas of sediment movement: sources, transport paths & sinks identified at local and site scales	Identification of local and site scale weather systems driving processes at a sediment cell scale	Water level regime at site level; Seasonal and inter-annual fluctuation in sea level; Nearshore wave & current patterns	Inter-annual resolution of the coastal sediment budget for cells at the planning scale

In the literature a sediment cell is defined as a reach of coast, including the nearshore terrestrial and marine environments, within which movement of sediment is largely self-contained (Mc Innes *et al.* 1998). Cells include areas of sediment supply, transport pathways and sediment loss from the nearshore system (Figure 2-2; Figure 2-3; Section 4.3.7). The definition of cells as being largely self-contained is not always applicable along much of the Western Australian coast.

Coastal sediment cell boundaries may be spatially fixed, because of the presence of rocky headlands or structures, or ambulatory with changing sediment transport conditions (Carter 1988). Sediment exchange across boundaries between adjacent cells occurs, but may be constrained and/or highly variable over time. When sediment exchange between adjacent cells is limited, cells may be used for estimation of a coastal sediment budget (Komar 1996; Rosati 2005). Significantly, this includes identification of areas undergoing erosion or accretion and the linkages between them. It provides a clear link between sediment budget estimation and coastal management (eg. Hooke *et al.* 1996; Cooper *et al.* 2001).

Whether morphologic changes within the cells reflect spatial variation in the coastal energy regime is highly probable but open to question. Herein, the cells have been used to structure identification of the geomorphic components of the coast and nearshore waters. Cells have also been used for comparative purposes to establish areas of relative stability along the coast.

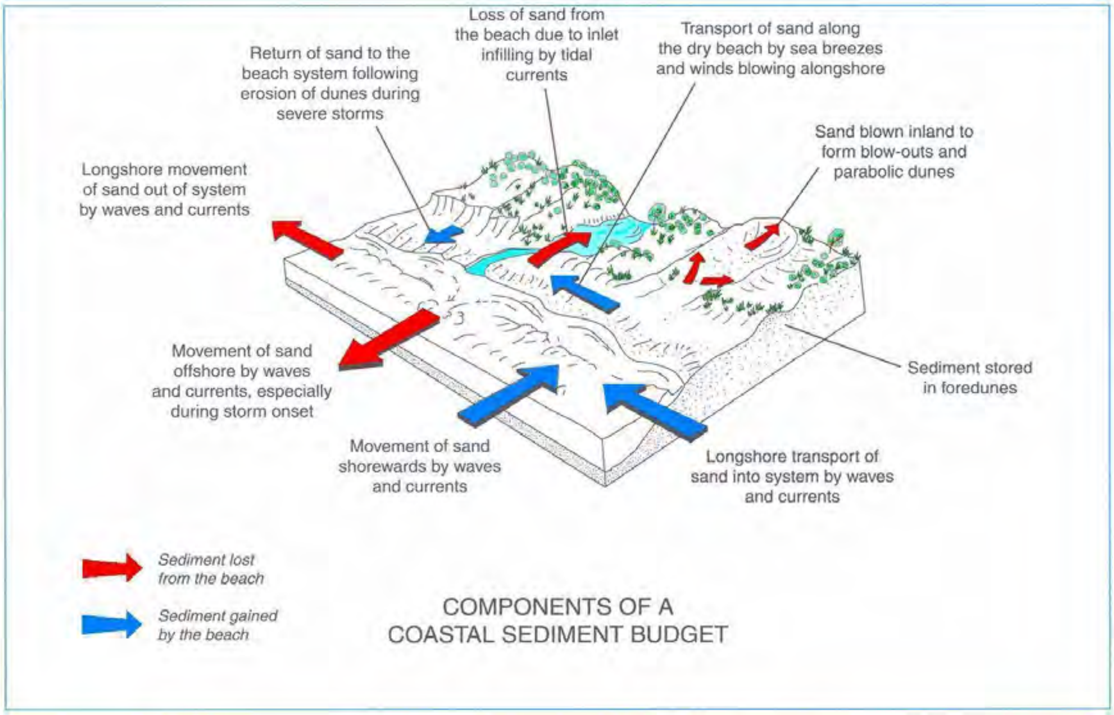


Figure 2-2: Sediment Budget Components
A Conceptual Sediment Cell in which the Components of the Sediment Budget Have Been Identified. Estimation of the volume of material for each component would contribute to determination of a sediment budget for the cell (Source: WAPC 2002)

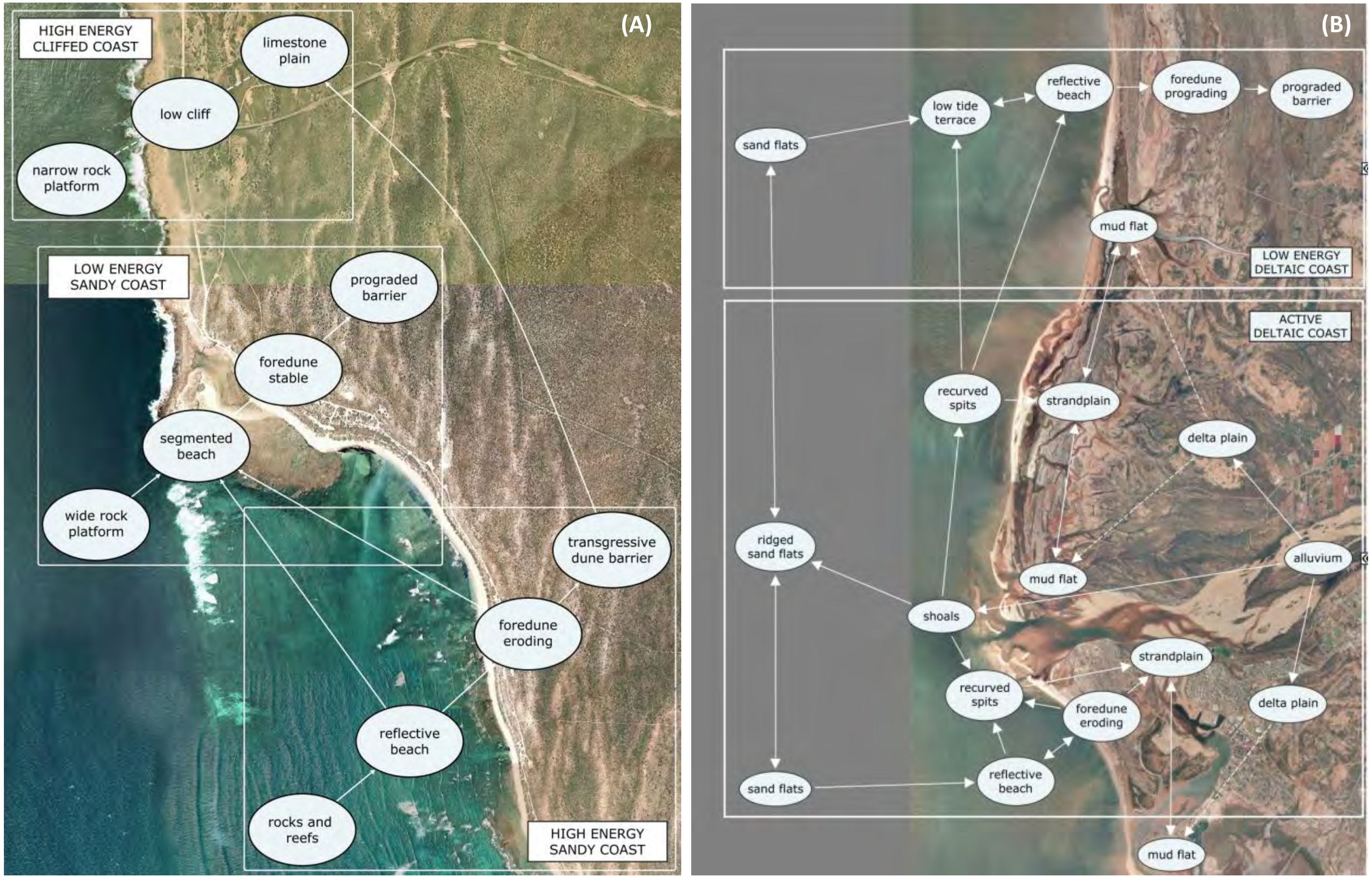


Figure 2-3: Sediment Budget Components for Example Sediment Cells

(A) Components of a Sediment Cell at Point Quobba; (B) Components of a Sediment Cell at the Gascoyne River mouth and Miaboolya Beach

2.2. LAND SYSTEM AND LANDFORM IDENTIFICATION

Land systems and landforms for parts of the Study Area previously have been described in a wide variety of plans, reports and technical papers, including:

- Coastal management plans (CALM & Shire of Shark Bay 1993; DEC & Conservation Council 2007)
- Coastal and marine conservation plans (CALM 1996, 2000, 2006; DEC 2008; DEWHA 2010; DEC & Conservation Commission of Western Australia 2010);
- Regional planning strategies (WAPC 1996, 1997, 1998; DPI 2004);
- Technical reports (Johnson 1974; Hesp & Morrissey 1984; Woods *et al.* 1985; Hocking *et al.* 1987; DPUD 1990; Hocking 1990; Playford 1990; SKM 2002; DAL Science & Engineering 2004; Russell 2004; Damara WA 2006a; Simpson *et al.* 2007; SKM 2007; Damara WA 2009; GEMS 2009; Gozzard 2012); and
- Scientific papers (Wyrwoll *et al.* 1993; Sanderson & Eliot 1996; Sanderson 2000; Short 2005).

These provide substantial insight into the variety and distribution of landforms along the coast, and some describe different sectors of coast based on landscape. Few cover large tracts of coast or have adopted a compartmental or sectoral approach to landform description as a basis for planning. However, they identify the major land systems and landforms present in the Study Area (Table 2-5) and have been used in the estimation of coastal vulnerability to metocean changes (Section 4).

Three areas of landform development are commonly identified. These are the nearshore, shore and onshore zones or components of the marine and coastal environment. Herein *nearshore* is determined by scale and refers to the offshore boundary of a compartment or cell; *shore* encompasses the shape of the shoreline in plan and its aspect or orientation with respect to dominant and/or prevailing wave directions, as well as the type of active beach present; and *onshore* refers to rocky coast and Holocene dune complexes as well as landforms of fluvial or tidal origin. A different suite of landforms may be identifiable at a regional, land system and landform scale for the same reach of coast.

Detailed maps of onshore landforms have been compiled for the Areas of Planning Interest (Figure 2-4) and used in the assessment of vulnerability at a sediment cell scale. Apart from that application, information relevant to landuse on *specific landforms* is outside the scope of this report. However, it may be derived from several sources for local area planning:

1. It may be extracted from the instability scores for each landform type used in estimating vulnerability. However, it should be clearly recognised that the level of landform classification provides only a basic measure of potential for change, and hence the information should be used with caution.
2. In some instances, more detailed estimates of landform stability may be compiled for places of particular planning or management interest, such as green field sites nominated for future development as rural urban areas or tourism development sites. Although the high resolution landform mapping offers further spatial refinement the stability of individual landforms within such classes is quite variable. For example,

frontal dunes subject to erosion by blowouts are considered to be less stable than fully vegetated, undisturbed frontal dunes in the context of the assessment, but are classified in the same landform category.

Detailed mapping of landforms and description of the conceptual models applied to them has been completed for the Western Australian coast between Cape Naturaliste and Kalbarri by the Geological Survey of Western Australia as part of the WACoast Project (Gozzard 2011a, b). This project is currently being extended to include the Gascoyne Region (Gozzard 2012).

Table 2-5: Major Landform Associations
(After: Searle & Semeniuk 1985; Semeniuk 1996a)

Cross-shore location	Landform
(1) Nearshore Morphology	Islands Gulfs Linear reefs and submarine ridges Pavements Basins and lagoons Sand banks Sand flats and seagrass meadows Sub-tidal terraces
(2) Landforms of the Shore	Shoreline shapes (straight, irregular, arcuate and zeta-form) Peninsulas and promontories Rocky coasts (cliffs, ramps and platforms) Beaches (sheltered and exposed forms) Deltas, rivers and alluvial flats Tidal flats and tidal creeks
(3) Onshore Landforms	Limestone plateaux and outcrops Deltas Estuaries Coastal lagoons and wetlands Inter-tidal flats and tidal creeks Barriers Foredunes Frontal dunes (blowouts and parabolic dunes)

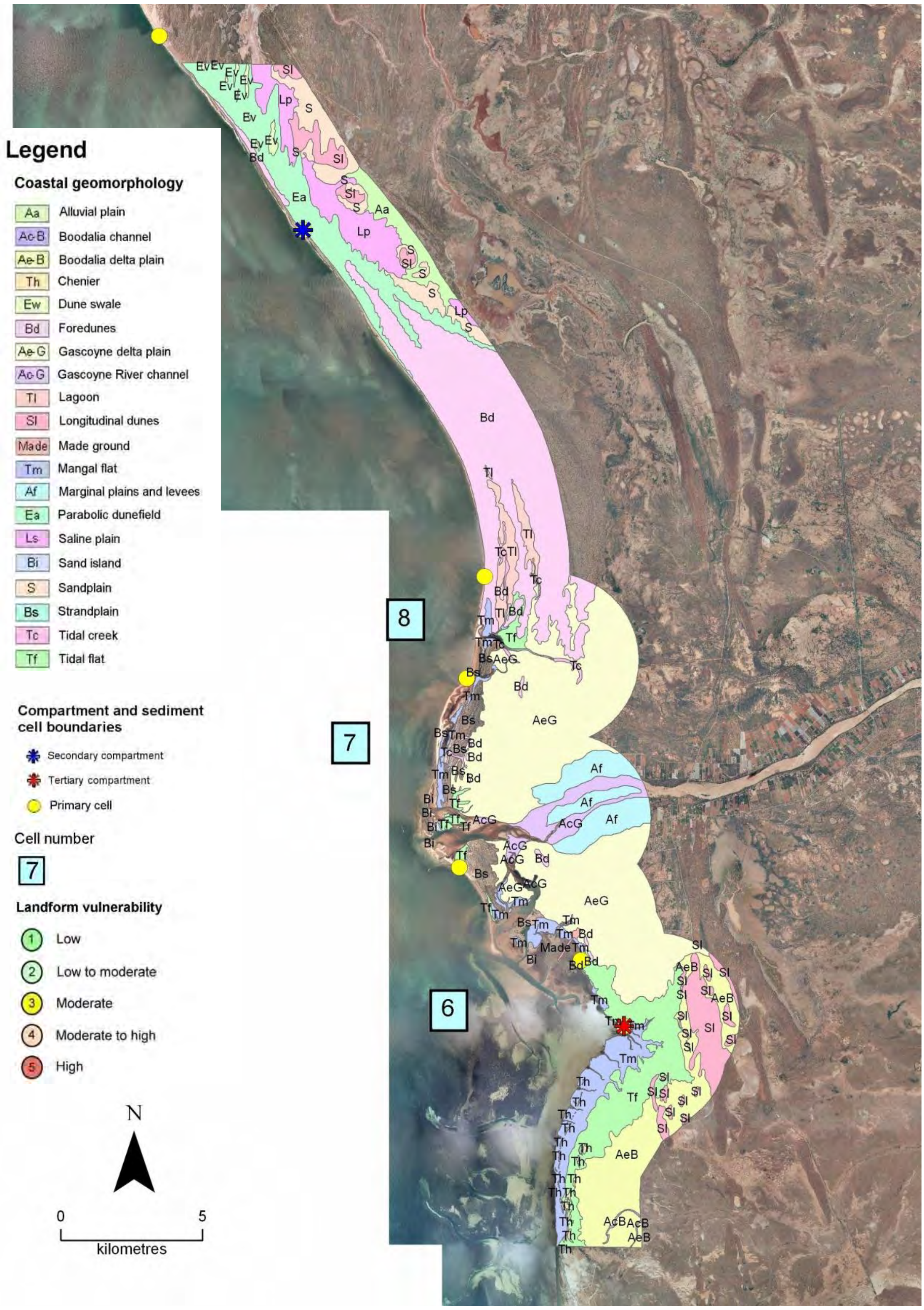


Figure 2-4: Landforms and Sediment Cells for Areas of Planning Interest in the Vicinity of Carnarvon and Miaboolya Beach

Landform Maps for all Areas of Planning Interest are in Appendix G.

2.3. RANKING LAND SYSTEM AND LANDFORM SUSCEPTIBILITY AND INSTABILITY

Landform associations common to the nearshore, shore and onshore zones of the coastal environment provide a basis to assess the susceptibility of the coast to change in the natural structure and the current stability of the landforms each structure supports. The land system structure and landform stability describing each ranking level have been taken from conceptual models described in the geological and geomorphological literature.

The rank of individual land systems and landforms indicates the likelihood of geomorphic change. A low rank (1) indicates a low risk of change to the natural structure or that the landforms on the geologic structure incorporating them currently have a low level of instability. Conversely a high rank (5) indicates the structure is likely to change or cause change over a planning horizon of 100 years, and that the landforms present are currently unstable. Rationale for the ranking is discussed below. The criteria used to rank susceptibility and instability of land systems and landforms of the Gascoyne coast are listed in Table 2-6.

Susceptibility ranking is based on five stages in the evolution of major land systems in response to long term (inter-decadal and longer) changes in metocean processes, brief but extreme high magnitude events or the cumulative effect of persistent short term changes to the land surface. In all instances the changes taking place may cross multiple zones of the nearshore, shore and onshore. Instability refers to a single landform or landforms associations on the land surface. It also is ranked on a five point scale based on comparison of current landform condition or changes taking place over less than a decade.

2.4. SUSCEPTIBILITY AND INSTABILITY

Susceptibility and instability are related concepts drawn from geological and geomorphologic literature respectively describing the evolution of disparate land systems, and landform change in response to metocean processes and change in sediment supply over different intervals of time. For this study, the relative importance of different processes has been considered with respect to eight land systems and landforms units. Key references considered in the evaluation of susceptibility and instability includes:

1. Cliffs: Trenhaile (1987); Sunamara (1992); Woodroffe (2003).
2. Coral Reefs: Hopley (1994); Woodroffe (2003); Collins & Twiggs (2011).
3. Sub-tidal terraces and tidal flats: Brown (1988); Semeniuk (1996a); Dyer *et al.* (2000); Woodroffe (2003); Morton & Holmes (2009); Davies & Woodroffe (2010); Toffolon & Lanzoni (2010).
4. Deltas, estuaries and rivers: Wright (1985); Perillo (1995); Brearley & Hodgkin (2005).
5. Cuspate forelands & Tombolos: Zenkovich (1967); Silvester & Hsu (1993); Sanderson & Eliot (1996); Sanderson (2000).
6. Barriers: Chapman *et al.* (1982); Cowell & Thom (1994); Roy *et al.* (1994); Hesp & Short (1999a); Masetti *et al*. (2008).
7. Beaches: Nordstrom (1980, 1992); Wright & Short (1984); Jackson *et al.* (2002); Short (2005); Eliot *et al.* (2006); Green (2008); Doucette (2009); Freire *et al.* (2009); Travers *et al.* (2010); Gallop *et al.* (2011).
8. Coastal Dunes: Semeniuk *et al.* (1989); Hesp & Short (1999a, b); Hesp (2002); Houser & Matthew (2011).

Table 2-6: Criteria for Landform Susceptibility and Stability in the Gascoyne

(A) SUSCEPTIBILITY (Potential for structural impacts)

NEARSHORE MORPHOLOGY (Depth<25m)	Rank
Continuous offshore reef OR Shallow lagoon OR Shelf (platform, terrace or bank)	1
Discontinuous offshore reef OR Deep lagoon OR Shelf (platform or bank)	2
Shallow intermittent reef OR Shallow broken pavement (Depth <10m)	3
Deep intermittent reef OR Deep broken pavement (Depth >10m)	4
Unconsolidated sediments in depth <10m OR Bare sand or seagrass banks	5
SHOREFACE STRUCTURE	
Sheltered, wide (>250m) sub-tidal terrace OR Cliff (>10m) plunging to sub-tidal level	1
Sheltered, narrow (<250m) sub-tidal terrace OR Cliff (>10m) & intertidal platform	2
Cliff (5 to 10m) & intertidal platform	3
Wide tidal flats (>5km wide) OR Beach rock or gently sloping rocky coast	4
Narrow tidal flats (<5km wide) OR Sandy shoreface on wave dominated coast	5
SHORELINE SHAPE & ORIENTATION (Mixed sandy & rocky coast)	
Straight or seawardly convex rocky coast OR South (SSE to SSW)	1
Irregular or rhythmic shoreline OR South West (SSW to WSW)	2
Arcuate or zeta-form, shallowly indented OR North (NNW to NNE)	3
Arcuate or zeta-form, deeply indented OR North West (WNW to NNW)	4
Cuspate forelands & tombolos OR West (WSW to WNW)	5
BARRIER, DELTAS OR OTHER STRUCTURE	
Episodic, Transgressive Barrier OR Dunes on supratidal rock surface (above high tide) OR Wave Dom. Delta: Mainly closed mouth	1
Prograded Barrier OR Perched beaches on intertidal rock surface OR Wave Dom. Delta: Intermittently open mouth	2
Stationary Barrier OR No Barrier – rocky coast OR Tombolo OR Wave Dom. Delta: Permanently open mouth	3
Receded Barrier OR Salient & Cuspate foreland OR River Dom. Delta: Inherited deltaic features	4
Mainland beach OR Narrow spit or chenier OR River Dom. Delta: Active delta & stream channels	5

(B) INSTABILITY (Current changes to land surface)

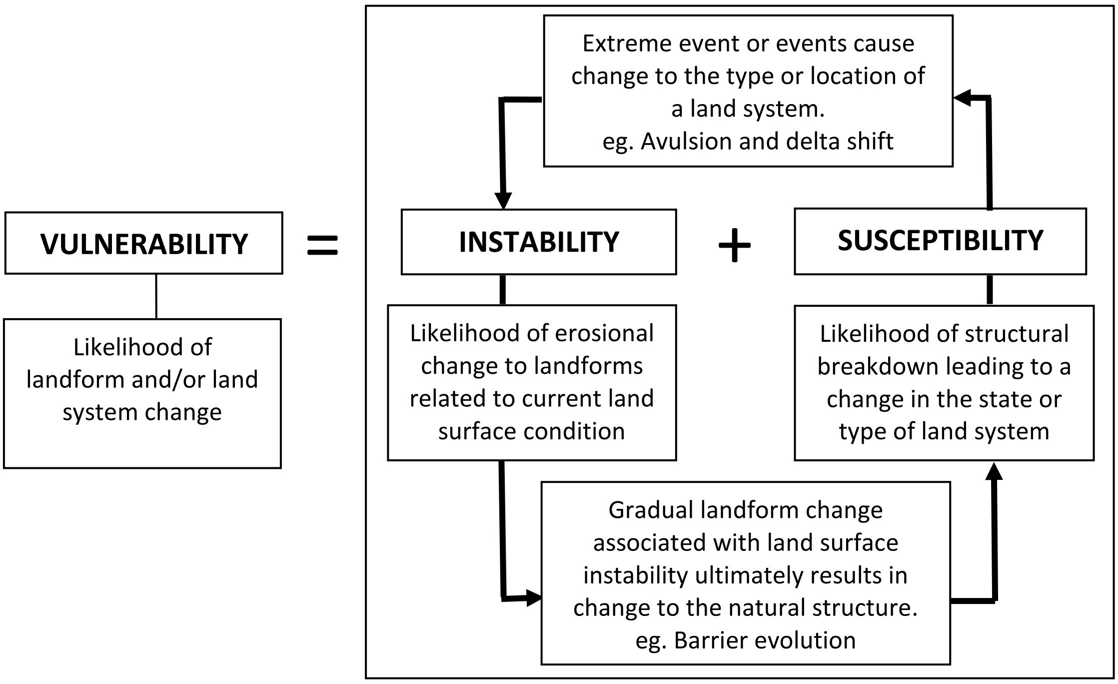
INSHORE SUBSTRATE (Depth <5m)	Rank
Hard rock (eg Granite) OR Greater than 75% reef or pavement	1
Moderately hard rock (eg Sandstone) OR 50 to 75% reef or pavement	2
Moderately soft rock (eg Limestone) OR 25 to 50% reef or pavement	3
Soft rock (eg Eolianite or calcarenite) OR Less than 25% reef or pavement	4
Bare sand surface: No rock outcrop	5
BEACHFACE MORPHOLOGY & PROFILE	
No beach OR Sheltered flat or segmented beachface OR Frontal dune on bedrock above high tide	1
Sheltered rounded beachface OR Perched beach on supratidal platform or beachrock	2
Exposed - reflective beachface OR Perched beach adjoining intertidal bluff	3
Exposed – transitional or dissipative beachface OR Perched beach on intertidal platform or beachrock	4
Exposed – high waves & cliffed coast OR Perched beach on shallow pavement	5
FRONTAL DUNE COMPLEX (+ Foredunes) OR TIDAL FLATS (Shoreline features)	
Continuous frontal dune & foredune ridges OR Foredune vegetation cover >75% OR Continuous lithified chenier ridge	1
Discontinuous frontal dune & foredune ridges OR Foredune cover 50 -75% OR Vegetated tidal flat margin with few tidal creeks	2
Partly scarped foredune OR Frontal dune vegetation cover 25 - 50% OR Vegetated tidal flat margin with many tidal creeks	3
Continuously scarped foredune OR Frontal dune vegetation cover <25% OR Discontinuous lithified chenier ridge	4
Frontal dune scarped OR Mobile sand sheet OR Bare tidal flats with surface run-off / tidal channels	5
BARRIER VEGETATION COVER OR TIDAL FLATS (Landward Features of the Surge Zone)	
No barrier OR Undisturbed dune sequence OR Fully vegetated (>75% cover on barrier) OR Wide Halophytic zone & narrow salt flats	1
50 to 75% vegetation cover on barrier OR <25% active dunes or bare sand OR Narrow Halophytic zone with broad salt flats & few tidal creeks	2
25-50% vegetation cover on barrier OR 25-50% mobile dunes OR Narrow Halophytic zone with broad salt flats & common tidal creeks	3
<50% vegetation cover on barrier OR 50-75% active dunes or bare sand OR Broad bare salt flats with Halophytic patches, palaeochannels & tidal creeks	4
Mobile sand sheets OR <25% vegetation cover on barrier OR Broad bare salt flats with residual mounds, palaeochannels & tidal creeks	5

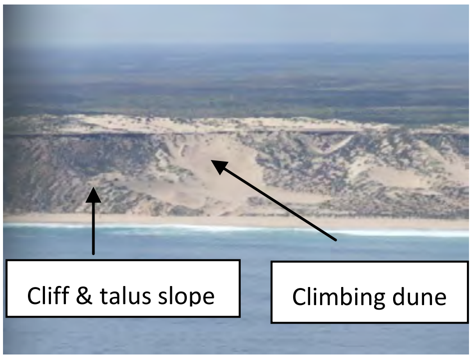
References such as those by Semeniuk (1996a) describing land systems on the Western Australian coast and Hsu *et al.* (2008) describing topographic control of the shoreline geometry have been used where appropriate and available. However there are gaps in knowledge, particularly with respect to mixed sandy and rocky coast where the geologic framework is a major factor.

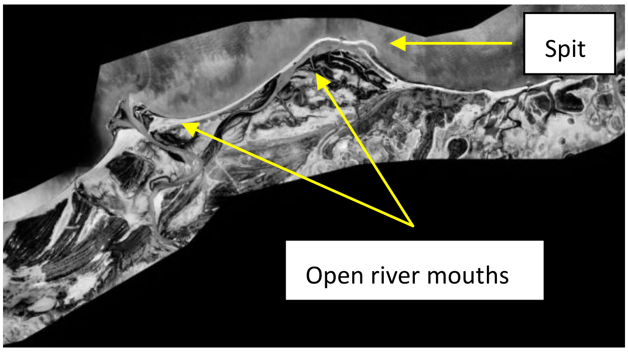
Together, the concepts of susceptibility and instability describe the *vulnerability* of coastal land systems and landforms to metocean change (Figure 2-5). Briefly, if current landform change is continued for long enough, exacerbated by natural changes in climate, or an extreme event occurs the land system on which the landform changes are taking place may reach a tipping point where the land system changes state. If a land system is susceptible to change it is highly likely that it is comprised or consists of or supports unstable, mobile landforms. For example a barrier system may be comprised of stable or unstable sand dunes where the current state of instability is evidenced by the proportion of the land surface under vegetation cover. Destabilisation of a barrier system on a stable coast may occur when barriers change from progradational to erosional forms as a result of prolonged loss of sediment from the coast (Roy *et al.* 1994; Hesp & Short 1999a; Masetti *et al.* 2008). Such large geomorphic changes have been modelled numerically, including modelling by Stive & de Vriend (1995), Cowell *et al.* (2003a, 2003b, 2006) and Stive *et al.* (2009).

The twin concepts of susceptibility and instability are linked by four key, interacting facets of the coastal environment: the geologic framework which supports the present landform systems; sediment compartments and cells in which the systems have developed; sediment supply to the cells and sediment accumulation or loss from the cells; and the resulting stability of landforms along the coast. These four components define large scale morphodynamic systems (Figure 2-6) and their interactions establish trends for changes occurring at all scales. Although linked by common metocean processes, coastal susceptibility and landform stability occur at disparate temporal and spatial scales; they have independent likelihoods of change and hence present different aspects of coastal vulnerability. These are combined in analysis ranking the vulnerability of different sections of coast, the compartments and cells.

Viewing metocean change and landform responses at a particular scale is a matter of convenience. In reality, the environment is dynamic at all scales with slower changes providing a long-term context for faster ones (Figure 2-7). Hence, metocean processes and landform change need to be considered at multiple scales. At the broadest evolutionary scale of coastal development it is pertinent to recall the vulnerability ranking for the overall land system, which is likely to include finer, more detailed features having a very different ranking. The level of vulnerability estimated at any scale should be set in the context of coarser and finer assessments of landform susceptibility to the natural variability of metocean drivers and the current condition (instability) of the land surface. At this scale the responses of individual landforms or landform elements to metocean events is apparent. Each scale provides an indication of management pressures likely to accord to land-use *within each whole cell* at that scale relative to others in a series described for a region or administrative coastal area.

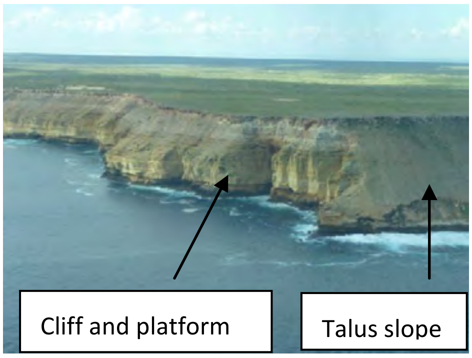


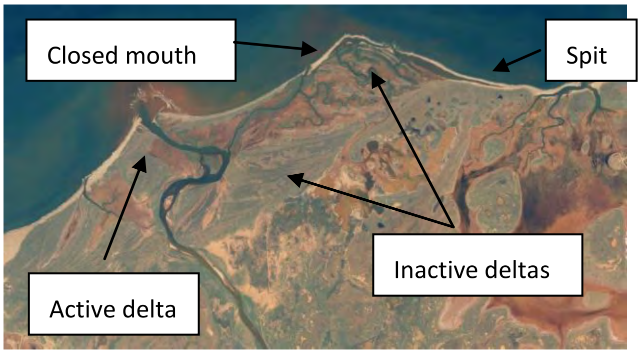




Above: Perched barrier and climbing dunes
Below: No barrier. Perched beach and old dunes

Above: Ashburton River Delta 1963
Below: Ashburton River Delta 2009





Incremental change: Gradual sediment loss from accretionary landforms such as beaches and foredune plains adjoining cliffs results in change to the natural structure, including loss of the barrier and exposure of the cliff.

Extreme event: Sediment of deposited during flooding of the Ashburton River after 1963 closed the eastern mouth and formed an elongate spit extending eastward from the river mouth. Subsequent migration of the spit is apparent by 2009.

Figure 2-5: Instability, Susceptibility and Vulnerability

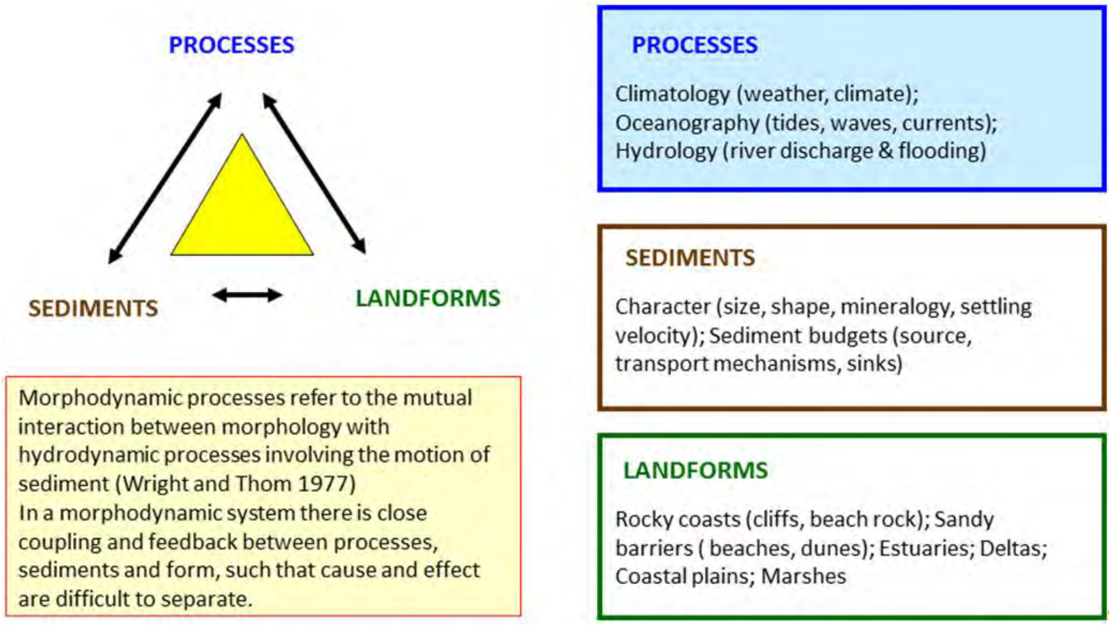


Figure 2-6: Components of a Morphodynamic System on a Sandy Coast

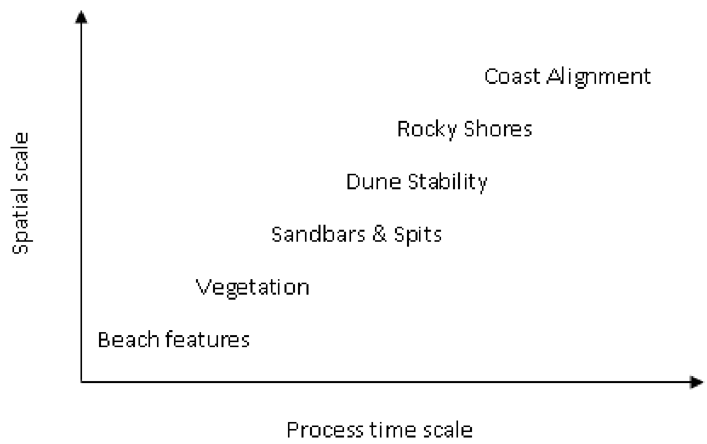


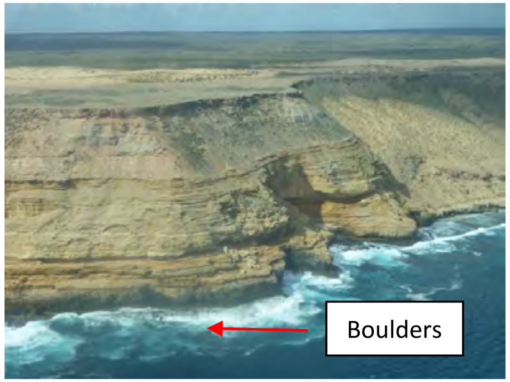
Figure 2-7: Scales of Coastal Change for Different Coastal Features

2.4.1. Land System Susceptibility

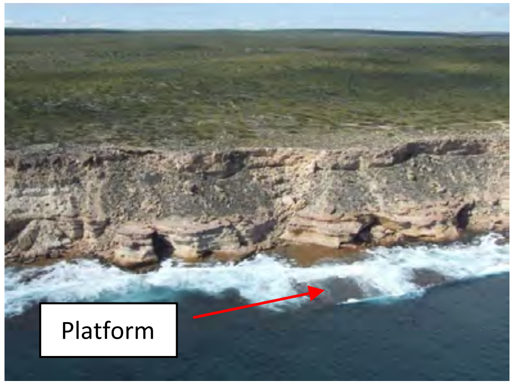
Estimation of the *susceptibility* of land systems to large-scale change in the natural structure is based on published descriptions of coastal evolution over the past 6,000 years; however the focus of the report is on large scale landform changes likely to occur over a planning horizon of 100 years. Some of these features are illustrated in Figure 2-8 to Figure 2-10. The generalised morphology and stratigraphy of different types of coastal sand barriers in eastern Australia has been described by Roy *et al.* (1994) with a more complex conceptual model of southern Australian barriers presented by Short (1988). More recently, Hesp & Short (1999a) have described barriers attached to or overlying cliffs. The conceptual models of Roy *et al.* (1994) and Hesp & Short (1999a) are illustrated in Figure 2-10. In this report attached barriers are referred to as perched barriers and the typology extended to include barriers overlying rock pavement, platforms and irregular bedrock surfaces as well as cliffs. These forms commonly occur around the coast of Western Australia.

2.4.2. Landform Instability

Landform *instability r*efers to the current condition of the land surface and changes taking place over short to medium time scales; those commonly occurring at less than interdecadal frequency. For the purposes of this study stability is indicated by current evidence of erosion, particularly on unconsolidated sandy coast. Examples of different levels of stability on similar landforms are illustrated in Figure 2-11 to Figure 2-13. On coastal sand barriers the instability includes historical shoreline movement, foredune washover, foredune destruction, scarping of the foredunes and frontal dunes, gullying, slumping, blow-out activity and migration of mobile sandsheets. Hesp (1988, 2002) presented a conceptual model of recurrent foredune development, destruction and reformation (Figure 2-12) which he related to shoreface processes. His observations, with those of Short (1999) are built on an understanding of the interaction of inshore, beach and dune processes, in which short-term variation in coastal stability is both affected by and affects the long-term evolution of the coast.

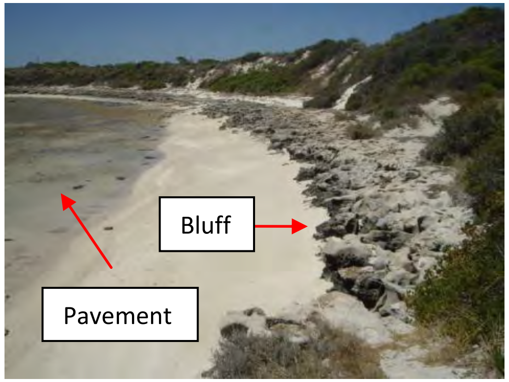


Rank 1: High cliff (>10m) plunging to sub-tidal level

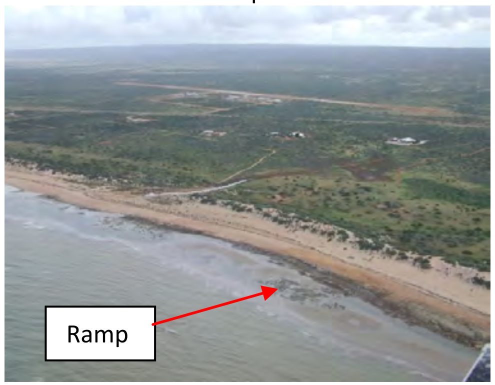


Rank 2: Moderate to high cliff (>10m) with an intertidal platform

Rank 3: Cliff (5 - 10m high)and wide intertidal platform



Rank 4: Rock pavement or intertidal platform and low bluff (<5m high)



Rank 5: Gently sloping rocky shore

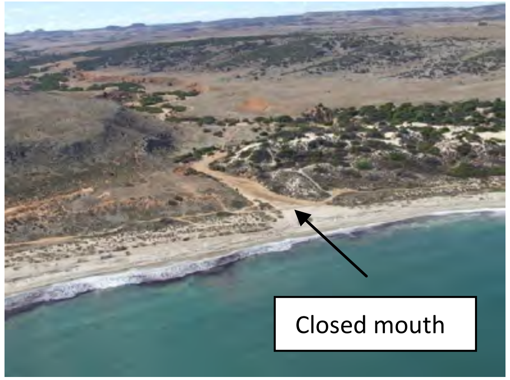
The *susceptibility* of rocky coast refers to the likelihood of a coastal land system or landform *structure* altering in response to projected change in metocean conditions over a long period,

Variation in structure may occur spatially, due to differences in rock type; or temporally due to differences in the rock strength and exposure.

The sequence illustrated here loosely follows that described by Sunamara (1992).

Each of the land systems shown may display different levels of instability depending on rock type, lithification and extent of weathering

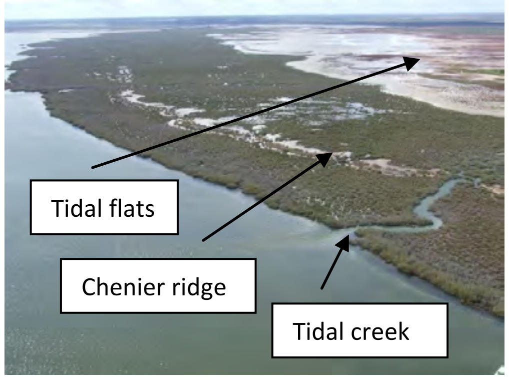
Figure 2-8: Susceptibility Rankings for Cliffs, Bluffs, Platforms, Pavements and Ramps



Rank 1: Wave Dominated Delta (WDD)
Mainly closed river mouth. Stream subject to intermittent flooding and discharge into the ocean.

Rank 2: Wave Dominated Delta (WDD)
Intermittently open river mouth. Breaching of the bar may result in sediment moved from ocean to estuary.

Rank 3: Wave Dominated Delta (WDD)
Mainly open river mouth. Tidal sediment exchange apparent. (Photo: Google Earth 2006)



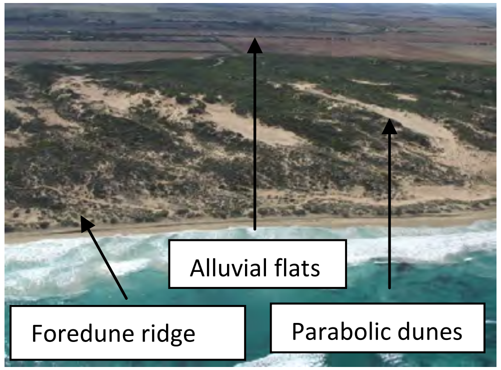
Rank 4: River Dominated Delta (RDD)
Inactive river delta, tidal flats & cheniers. Mangroves are apparent along the delta margin.

Rank 5: River Dominated Delta (RDD)
Active delta & stream channels (Photo: J. Dodson). Mangroves on estuarine floodplain.

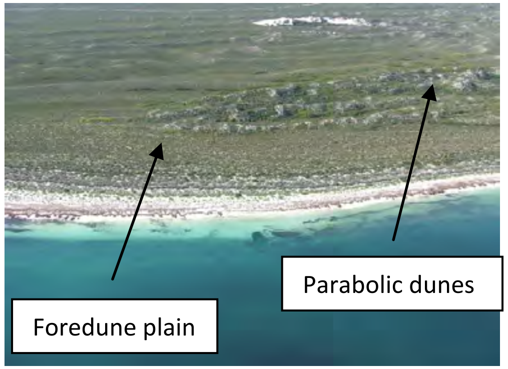
The *susceptibility* of river delta refers to the likelihood of the landform *structure* altering in response to projected change in metocean conditions, particularly sea level.

Variation in structure occurs spatially in response to a wide variety of interactions amongst geology, sediments, landforms and metocean processes, such as those described by Perillo (1995).

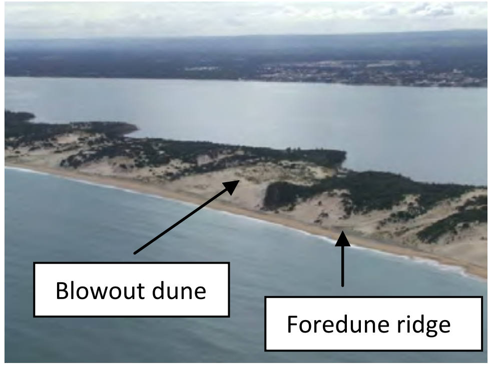
Figure 2-9: Susceptibility Rankings for River Deltas, both Wave and River Dominated Systems



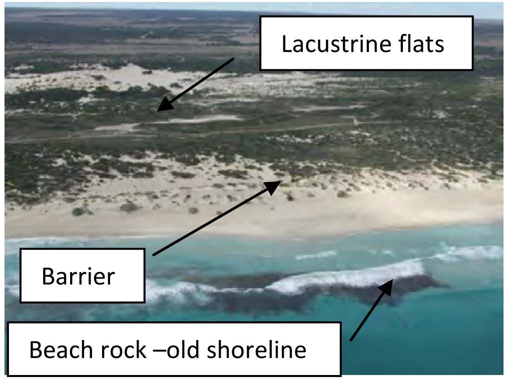
Rank 1: Episodic Transgressive Barrier
High ridge of nested blowouts and parabolic dunes. Here they abut and overlie alluvial flats.



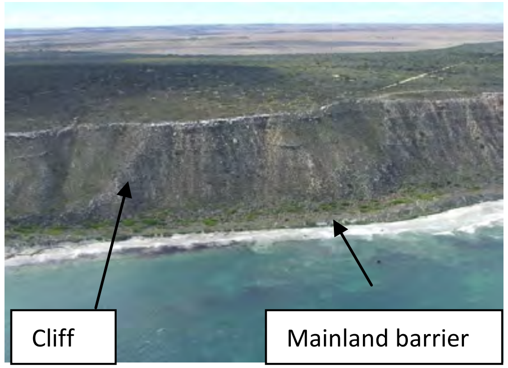
Rank 2: Prograded Barrier
Low plain comprised of foredune ridges. In this instance the plain abuts and older dune field.



Rank 3: Stationary Barrier
Low or narrow ridge of blowouts and parabolic dunes



Rank 4: Receded Barrier
Low narrow dune ridge with older sediments exposed along the shore



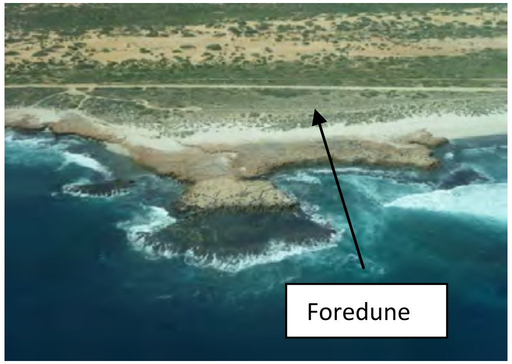
Rank 5: Mainland Beach
Narrow foredunes and beach abutting bedrock. Dunes may not be present in some circumstances.

The *susceptibility* of a sandy barrier refers to the likelihood of the *natural structure* altering in response to projected changes in metocean conditions.

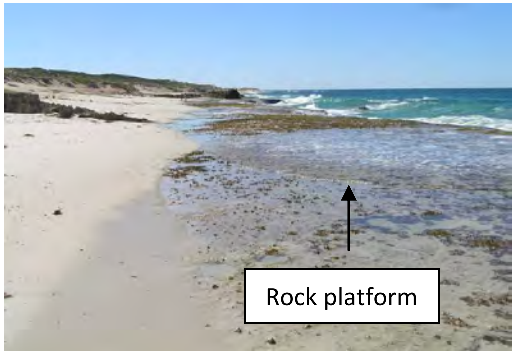
Barrier formation occurs over a long period, commonly millennia, although change in the natural structure from one type to another may occur within tens to hundreds of years.

The sequence illustrated here broadly follows that described by Roy *et al* (1994)

Figure 2-10: Coastal Shoreface Structures, Land Systems and Susceptibility Rankings for Barrier Systems (After Roy *et al.* 1994)



Rank 1: No beach OR a foredune is located on rock above the Highest Astronomical Tide (HAT) level



Rank 2: Perched beach is located on a supratidal rock platform close to the Highest Astronomical Tide level

Rank 3: Perched beach adjoining a low bluff extending above high tide level

Rank 4: Perched beach on an intertidal platform or beachrock ramp

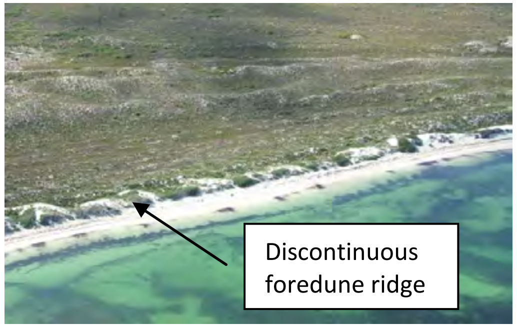
Rank 5: Perched beach on shallow inshore pavement

The ranked sequence shows beaches subject to increasing exposure to wave action and sea level fluctuation

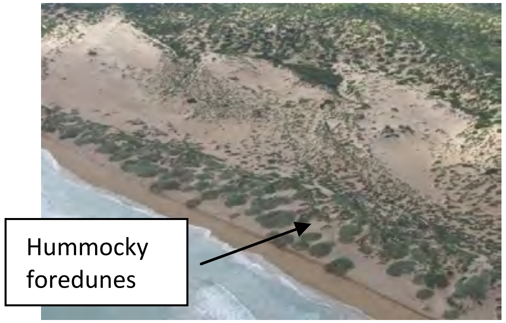
Figure 2-11: Stability of Perched Beaches
(After: Green 2008 & da Silva 2010)

Estimates of beach *instability* are based on the exposure of the beach to metocean processes. The variability of sandy beaches in different settings has been described by Nordstrom (1992) and Short (2005). The stability of sandy beaches perched on rocky substrates is not as well known, although such beaches are common features of the Australian coast.

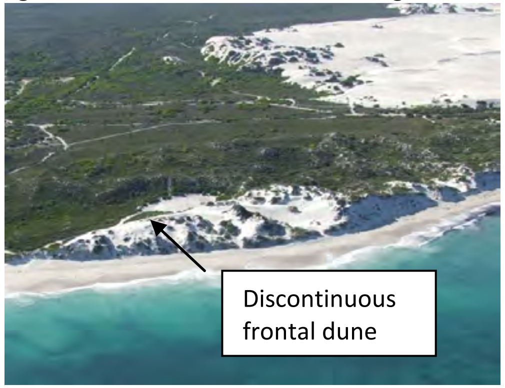
Rank 1: Continuous foredune and frontal dune ridges; Vegetation cover on the foredune ridge is >80%.



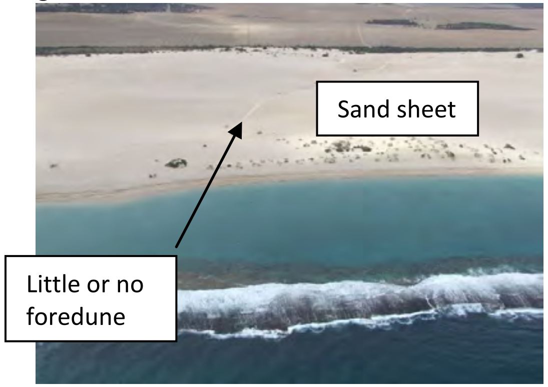
Rank 2: Discontinuous foredune ridge; small blowouts; vegetation cover on the foredune 50 to 75% cover.



Rank 3: Partly scarped foredune ridge: vegetation cover 25 to 50%; Small to moderate size blowouts



Rank 4: Continuously scarped foredune OR partly scarped frontal dune; vegetation cover <25%



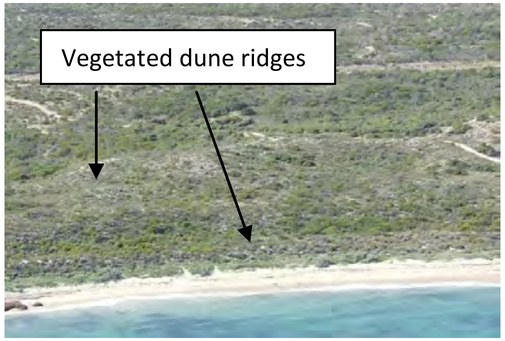
Rank 5: No foredune; scarped frontal dunes; beach directly connected to mobile sand sheet.

Estimates of *instability* are based on the land surface condition and the proportion of area in a compartment or cell that is currently bare sand or subject to erosion.

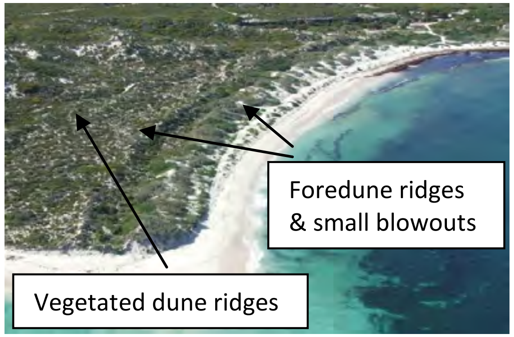
Destabilisation of dunes commonly occurs with destruction of a foredune, formation of blowouts and landward migration of the sand sheets, after which the foredune may reform. The quasi-cyclic changes take place in less than 50 to 100 years.

The ranked sequence illustrated follows the pattern of foredune destruction reported for Scarborough (Eliot & Clarke 1984) and elsewhere by Hesp (1988, 2002).

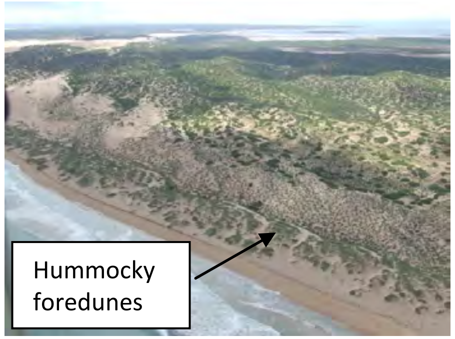
Figure 2-12: Stability of the Foredune & Frontal Dune Complex



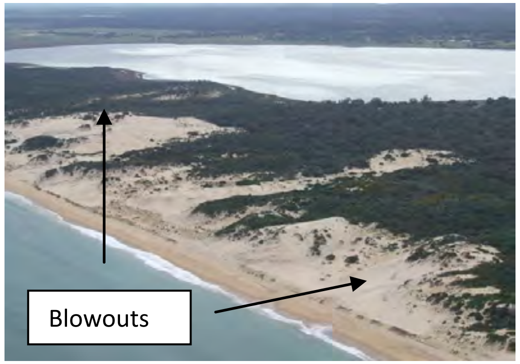
Rank 1: Gently undulating, continuous ridges of nested blowouts and parabolic dunes; Vegetation cover on the barrier is >75%.



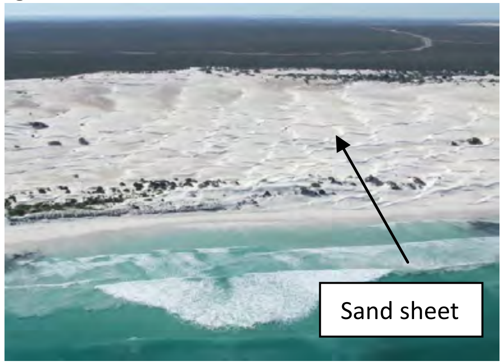
Rank 2: Complete ridges of nested blowouts and parabolic dunes with <25% active. Minor variation in vegetation cover on the barrier with >75% cover



Rank 3: Hummocky topography: 25 to 50% mobile dunes. Small to moderate size blowouts; Complete ridges of nested blowouts and parabolic dunes.



Rank 4: 50 to 75% active dunes or sand sheets
Active blowouts, parabolic dunes & sand sheets; diverse topography with 25 to 50% vegetation cover



Rank 5: Mobile sand sheets
Large blowouts, deflation basins, remnant knobs, & sand sheets; <25% vegetation cover on the barrier

Estimates of *instability* are based on the land surface condition and the proportion of area in a compartment or cell that is currently bare sand or subject to erosion.

Destabilisation of dunes occurs with destruction of a foredune, scarping of the frontal dunes or removal of the vegetation cover. The changes take place in a short period, commonly sub-decadally.

The sequence illustrated ranges from fully vegetated to active sand sheet without vegetation cover and broadly follows that described by Short (1988).

Figure 2-13: Dune Stability on an Episodic Transgressive Barrier

2.5. ESTIMATION OF VULNERABILITY

In summary, steps to derive an estimate of vulnerability for each compartment or cell were as follows:

Step 1: Landform descriptions incorporating the criteria used to separately describe the susceptibility and instability of a compartment or cell were compiled for the inshore, beachface and backshore, as well as the shoreline. An example for a cell in the Gnaraloo area is provided in Table 2-7. Descriptions of landforms for each of the secondary compartments along the Gascoyne coast are in Appendix E.

Step 2: A five point ranking was determined for each of the criteria used (Table 2-6);

Step 3: The rank scores for the susceptibility and instability criteria were separately ordered into four zones (Table 2-8) and summed for each planning unit;

Step 4: The likelihood of geomorphic change in susceptibility or instability was assigned a likelihood rank of low, moderate or high, for total susceptibility or instability rank scores of 4 to 9, 10 to 14 and 15 to 20 respectively; and

Step 5: The likelihood ranks were then combined to identify the indicative or relative vulnerability of each planning unit (Table 2-9). The steps used to combine the ranks are described in Section 2.6.

Table 2-7: Landform Descriptions for an Example Sediment Cell
The descriptions are intended to facilitate determination of the susceptibility and instability rankings from Table 2-9

Cell	S	N	INSHORE	SHORE	BACKSHORE
14	Gnaraloo Bay South	Gnaraloo Bay North	Due to a change in orientation of the coast there is a gap in the fringing reef which is further offshore and deeper in this cell. It again closes with the coast near Gnaraloo Bay North. The inshore lagoonal waters are <5m deep and the seabed includes patches of reef and sand, with an increasing proportion of intermittent reef and lagoonal pavement with distance along the coast.	Gnaraloo Bay is a zeta-form bay. The deeply indented southern section faces N to the break in the fringing reef. The straight section of shore faces NW and is rejoined by fringing reef. The beach is continuous. Its profile changes from a flat profile in the sheltered NW flank of the cuspate foreland to more exposed reflective and transitional forms with distance around the bay. However, the proportion of beach perched on beachrock ramps also increases to the northeast.	The cell has a narrow, receded or mainland barrier form away from the foredune ridges that comprise the cuspate foreland. A narrow, moderately high (5 to 10m) foredune ridge abuts and overlies an older sandplain surface. The seaward face of the foredune ridge is increasingly steep and becomes more discontinuous and scarped with distance north. The ridge also widens from <50m to approximately 400m in the lee of the fringing reef. Much of the wider ridge complex is a bare sand sheet.

Table 2-8: Coastal Zones Used to Collate the Scores on Criteria for Ranking of Susceptibility and Instability

	SUSCEPTIBILITY	INSTABILITY
1	Nearshore Morphology (Depth <25m)	Inshore Substrate (Depth <5m)
2	Shoreface Structure	Beachface Morphology and Profile
3	Shoreline Shape and Orientation	Frontal Dune Complex and Tidal Flat Margins
4	Barriers, Perched Beaches and River Deltas	Vegetation Cover on Barriers or Tidal Flats

Table 2-9: Cell Susceptibility, Instability and Vulnerability Ranking for Cells in the Gnaraloo Area
A similar table is used to compile rankings for individual compartments

Sediment Cell	Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
14	Gnaraloo Bay South to Gnaraloo Bay North	3	4	3	4	14	**M**	2	3	3	3	11	**M**	3	**M**
13	Gnaraloo North to Gnaraloo Bay South	1	3	2	4	10	**M**	1	2	3	2	8	**L**	2	**L-M**
12	Gnaraloo South to Gnaraloo North	1	2	3	4	10	**M**	2	2	3	3	10	**M**	2	**M**
11	Red Bluff to Gnaraloo South	3	2	3	1	9	**L**	3	3	4	4	14	**M**	2	**L-M**

2.6. INTERPRETATION OF VULNERABILITY RANKING

The susceptibility and instability rankings have been interpreted by combining the susceptibility and instability rankings for each compartment or cell as follows:

- First, the susceptibility value assigned to a compartment or cell provides an estimate of the integrity of the natural structures based on the developmental state of similar natural structures elsewhere. This enables comparative estimate of the likelihood of change over a 100 year planning horizon for compartments or cells within the coastal area of interest. The implications of the comparison in which the susceptibility of each compartment or cell is assigned a low, moderate or high likelihood of occurrence are shown in Table 2-10a.
- Second, landform instability is comparatively ranked according to the current state of the land surface in each compartment or cell, which provides an estimate of the likelihood of landform change within the next decade. Again, the estimates are assigned a low, moderate or high likelihood of occurrence and are shown in Table 2-10b.
- Third, for each compartment or cell the susceptibility and instability ranks are combined in a matrix in which the combined likelihood of short to long term changes provide a five-fold estimate of vulnerability (Figure 2-14). In turn the vulnerability rankings derived from the matrix have been interpreted as a combination of those for susceptibility and instability (Table 2-11).

Under the State Coastal Planning Policy (WAPC 2003) coastal planning is required to address potential hazards and risks associated with coastal erosion and landform instability. The risk to people and property arise from the hazards presented by coastal change, which in turn relates to the vulnerability of the coast. Interpretation of the vulnerability rank is indicated in Table 2-11 in which constraints indicated by the likelihood of coastal change are identified and the implications of vulnerability rankings for coastal management indicated.

Table 2-10: Implications for Coastal Management

(a) SUSCEPTIBILITY (Long-term integrity of the natural structure)

Susceptibility Scores	Indicative Susceptibility	Site Implications
4 - 9	Low	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.
10 – 14	Moderate	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.
15 - 20	High	Natural structural features are extensively unsound. Major engineering works are likely to be required.

(b) LANDFORM INSTABILITY (Current condition of the land surface)

Instability Scores	Indicative Instability	Site Implications
4 - 9	Low	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).
10 - 14	Moderate	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).
15 - 20	High	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).

Separating susceptibility and instability is a device to qualitatively examine overall coastal stability, herein defined for the purposes of the report as vulnerability. As they are applied in the report, the twin concepts identify disparate aspects of stability, both of which should be considered in coastal planning and management. Hence, the susceptibility of a geomorphic structure to change and its present instability condition should not be used separately in risk assessment. The various combinations of susceptibility and instability rankings to yield the five vulnerability ranks are listed in Table 2-12 together with their implications for coastal management and the degree of risk represented by each level of vulnerability.

			INSTABILITY (CONDITION) (Existing morphologic change to land surface)		
			Low (Stable)	**Moderate**	**High (Unstable)**
			Example		
SUSCEPTIBILITY (STRUCTURE) (Potential change to geological structure)	**Low**	Barrier perched on extensive tracts of coastal limestone	(1) Vegetated swales in parabolic dunes landwards of a vegetated frontal dune ridge overlying coastal limestone above HWL	(2) Vegetated dunes landwards of a vegetated frontal dune ridge and perched on coastal limestone at HWL	(3) High foredune ridge and/or vegetated foredune plain overlying coastal limestone below HWL
	Moderate	Weakly lithified barrier with intermittent limestone outcrops	(2) Mainly vegetated swales in parabolic dunes landwards of a mainly vegetated frontal dune ridge	(3) Vegetated dunes landwards of a mainly vegetated frontal dune ridge (25 to 75% cover) and overlying coastal limestone	(4) Cliffed or discontinuous foredune fronting moderate numbers of mobile blowouts and sand sheets (<50% of the alongshore reach)
	High	Barrier comprised wholly of sand. No bedrock apparent along shore or in dunes	(3) Swales in parabolic dunes landwards of a partly vegetated frontal dune ridge	(4) Mainly vegetated dunes landwards of a partly vegetated frontal dune ridge with <25 to 75% cover.	(5) No foredune. Eroded frontal dune with numerous mobile blowouts and sand sheets (>50% of the alongshore reach)

KEY	Combined estimate of vulnerability
(green)	Low
(light green)	Low-to-moderate
(yellow)	Moderate
(peach)	Moderate-to-high
(red)	High

Figure 2-14: Indicative Vulnerability Matrix for a Mixed Sandy and Rocky Coast Based on Combined Estimates of Risk for Susceptibility and Instability

Table 2-11: Implications of Vulnerability Rankings for Coastal Management

Rank	Likelihood	Constraint
L	Coastal risk is unlikely to be a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.

Table 2-12: Combining the Coastal Rankings and Implications for Coastal Management

Susceptibility		Instability		Vulnerability		
	Implications		Implications		Risk	Rationale
L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).			
H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).			
L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah and Geraldton).			
M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah and Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).			
H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah and Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.

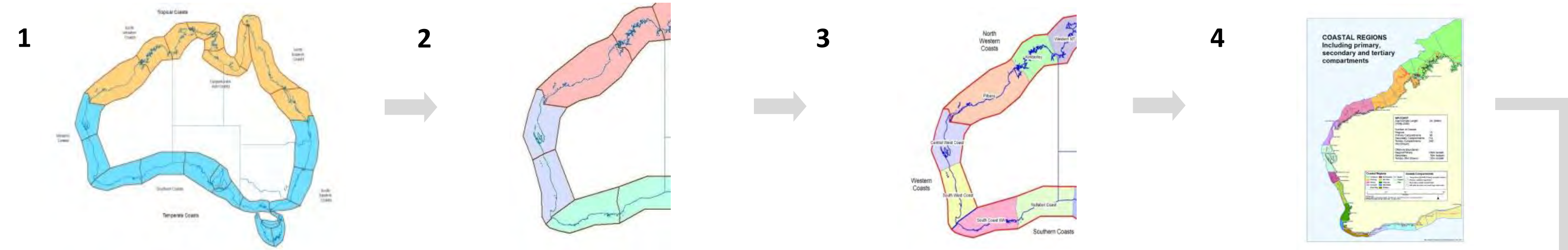
3. Regional Context: Land Systems and Landforms

The hierarchy of compartments used to identify the planning units generally accords with the terrestrial land systems described by van Gool *et al.* (2005) for soils in the agricultural arfeas of Western Australia. In this report, provinces are approximately equivalent to WA coastal regions; zones to primary compartments; land systems to secondary compartments; landform to tertiary compartments and sediment cells; and landform elements to sediment cells (Figure 3-1). At each scale an individual compartment has an association of landforms and processes that distinguishes it from its neighbouring compartments. However, within each of the three primary compartments the scales are dynamically linked by common morphology, processes and sediments and comprise a single morphodynamic system (Figure 3-2).

Impacts of environmental change at any level potentially may affect the whole system depending on the extent and intensity of change and the time over which it operates. Ramifications of this are that it is advisable to holistically consider potential impacts of a proposed development at a land system level first, scaling down to sediment cells and individual landforms as finer detail is required. Coastal susceptibility to environmental change is critical at a primary and secondary compartment scale, with the latter being examined here. Conversely, the condition or stability of landforms is most relevant to investigation of tertiary compartments and sediment cells, the latter of which have been used in the examination of Areas of Planning Interest.

In both contexts, an objective of this report is to indicate the principal geologic, geomorphic and metocean factors contributing to the relative vulnerability of sediment cells along the coast and further develop the applications listed in Table 2-4 by integrating the marine and terrestrial components of the land system. This is the rationale underlying consideration of nearshore features in assessing coastal vulnerability (Table 2-6).

At a broad provincial scale, the semi-arid coast of the Gascoyne region constitutes the Central West Coast Province of the West Coast Division (Figure 3-2). The coast is affected by a variety of weather systems commonly including anticyclonic high pressure systems, extra-tropical cyclones, strong seabreezes and occasional tropical cyclones (Section 4.2.1). Climatologically, the province is in a transitional zone and its northern boundary is at the boundary between the Temperate and Tropical Coast Regions. The frequency of tropical cyclones increases with distance north in the Study Area. Peak frequencies of tropical cyclones are recorded in the Pilbara between Karratha and Onslow, adjacent to the northern reaches of the Exmouth Gulf (Damara WA 2008).

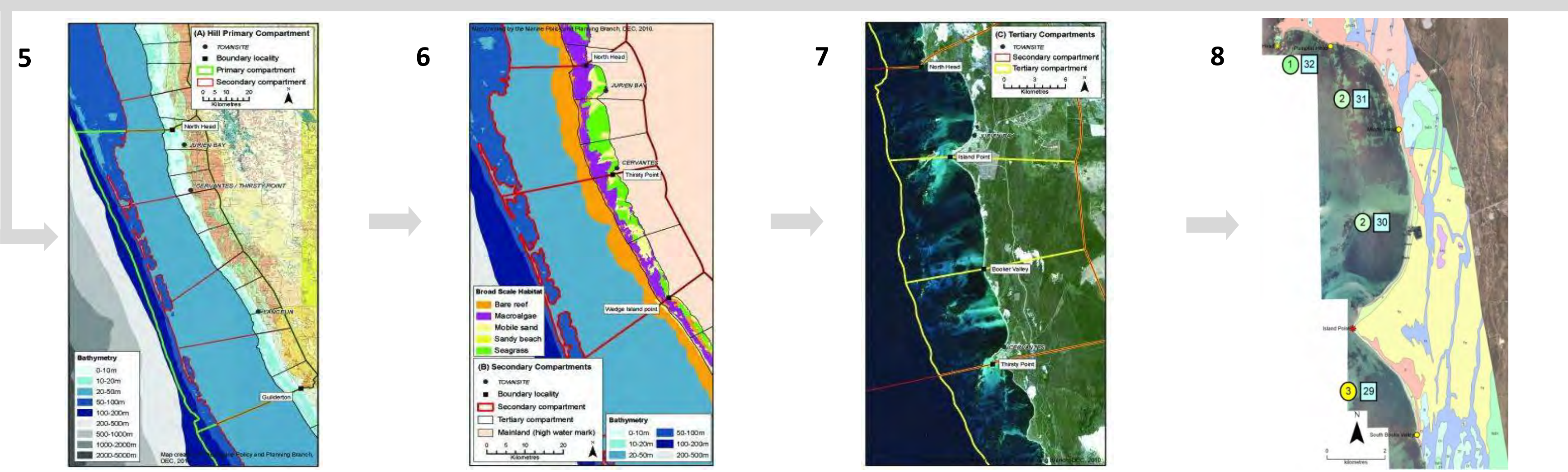


Zones: Broad sectors of the Australian continent based on climate

Divisions: Provides an overview of the whole state suitable for maps at scales of about 1:5,000,000

Provinces: Areas defined on geomorphologic or geological criteria suitable for regional perspectives at scales of about 1:1,000,000

Regions: Areas with recurring patterns of landform and geology suitable for regional mapping at scales of approximately 1:250,000



Land Systems (1): Areas of characteristic landform patterns suitable for mapping at regional scales of 1:100,000 to 1:250,000.

Land Systems (2): Areas of characteristic landform patterns suitable for mapping at regional scales of 1:50,000 to 1:100,000

Landforms (1): A local unit based on one or more definite landforms suitable for mapping at scales of about 1:25,000 to 1:50,000

Landforms (2): A local unit based on one or more definite landforms suitable for mapping at scales of about 1:10,000 to 1:25,000

Figure 3-1: Coastal Land Systems Hierarchy

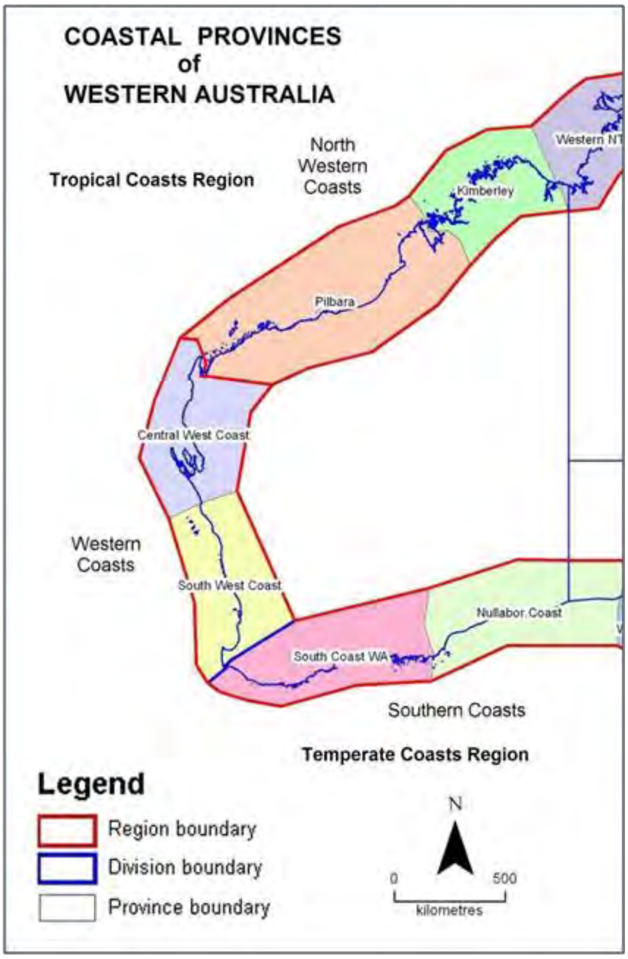


Figure 3-2: Coastal provinces in Western Australia

3.1. THE GEOLOGIC FRAMEWORK

At all scales, the geologic framework is a highly significant attribute of the Study Area. It is a primary determinant of the susceptibility of the coast to change through its interaction with marine processes and by provision of a foundation to the more recently formed Holocene landforms. At a secondary compartment level, or more detailed scale, tracts of coast may have landforms comprised of unconsolidated sandy sediments that overlie, or are perched, on a near continuous limestone or sandstone surface well above present sea level. However the rock basement, particularly that formed by the coastal limestone, is uneven in planform, hardness, elevation and depth below the unconsolidated sands. There is considerable diversity in the limestone topography and hence diversity in the susceptibility of the coast to change due to metocean forcing. The variability can be addressed in the planning process by a requirement for geotechnical or geophysical investigations in areas where they are justified by the value of proposed development or the need to protect existing infrastructure close to the shore.

Cleary *et al*. (1996: 250) stressed the role the inherited geologic framework plays in determining shoreface dynamics, dynamics of the area in which wave energy is mostly expended; the evolution of coastal sediment cells; and the development and morphology of unconsolidated accretionary landforms such as barriers and cuspate forelands. They pointed out that:

"…coastlines with limited sand supplies are also significantly influenced by the geological framework occurring underneath and seaward of the shoreface. For example, many US east coast barrier islands are perched on premodern sediments. The stratigraphic section underlying these perched barriers commonly controls the three-dimensional morphology of the shoreface and strongly influences modern beach dynamics, as well as sediment composition and sediment fluxes.

First, perched barriers consist of thin and variable layers of surficial beach sands on top of older, eroding, stratigraphic units with highly variable compositions and geometries. Depending upon composition, the underlying platforms can act as a submarine headland forcing different responses to shoreface dynamics that will dictate the nature of the shoreface profile. Stratigraphically controlled shorefaces are often composed of compact muds, limestones, or sandstones. Such lithologies exhibit a greater effect upon both the planform of barriers and morphology of the shoreface than those composed of unconsolidated materials. Second, along many parts of the inner shelf, bathymetric features that occur modify incoming energy regimes, affecting the patterns of erosion, transport, and deposition on the adjacent shorelines."

Their observations are applicable to most of the coast of Western Australia. They are especially relevant to the Gascoyne coast because a large proportion of the unconsolidated coastal landforms in the Study Area are of Holocene origin and overlie, or are perched on irregular rocky topography of older Quaternary origin. In many instances the Holocene deposits occur as small receded barriers that have retreated landwards and exposed the bedrock inshore or along the active beach. The underlying topography is mainly comprised of limestone or sandstone. It provides the framework in which the coast is developing through its interaction with sandy sediment and coastal processes. The interaction is fundamental to the manner in which the coast has evolved and will continue to develop. It also determines the susceptibility of the coast to future environmental change.

At a local scale the presence or absence of shoreface topography, particularly limestone and coral reefs have a significant effect on beach responses to storms and inshore processes. Cleary *et al*. (1996) pointed out that limited data exists on the interrelationships between the underlying geological framework and the morphology, sediments and evolution of coastal systems, although the wave and current dynamics of the shoreface determine how the adjacent shoreline and beach will respond to storms, and ultimately to the effects of rising sea level. Since then McNinch & Drake (2001) have described the influences of underlying geology on nearshore and shoreline processes in the United States. Their observations have been supported by List *et al*. (2002) through evaluation of the persistence of shoreline change hotspots along the northern coast of North Carolina; and by Bender & Dean (2002) in a review of wave field modification by bathymetric anomalies and resulting shoreline changes.

Understanding the processes and three-dimensional geologic framework that govern the shoreface characteristics is vital to determining the behaviour of beaches. It is an especially important consideration in the context of this report for two reasons. Firstly, Clearly *et al*. (1996) and others (Pilkey *et al*. 1993; Cooper & Pilkey 2004) have argued it negates application of the Bruun Rule (Bruun 1983, 1988), which has been widely applied in the calculation of setback to development on mixed sandy and rocky coast in Western Australia (WAPC 2003). Secondly, Silvester (1974), Hsu & Evans (1989) and Sanderson (2000) have discussed the roles of shoreface topography in determining the plan shape of beaches and the development of cuspate forelands. Their observations indicate it may be useful to consider the probable responses of specific coastal landforms to changing metocean processes as a more appropriate means of assessing potential coastal responses to projected environmental change in sea level or climate given that Bruun (1983) stated similar reservations with the application of his model.

3.1.1. Geology

The Carnarvon Basin is an epicratonic, faulted and gently folded Phanerozoic basin located at the southern end of the North West Shelf of Australia. It is elongated north-south, and contains mainly marine sediments of Ordovician-Silurian age to Recent. The Carnarvon Basin is transitional southwards into the Perth Basin and northeastwards into the offshore Canning and Roebuck Basins.

In the Southern Carnarvon Basin, most major structural elements are north trending and define a set of sub-basins (Gascoyne, Merlinleigh, Byro and Bidgemia) that contain up to 7km of predominantly Palaeozoic sediments with a Mesozoic veneer, which thickens to the north and west. Faults trend northerly and northwesterly. In the Northern Carnarvon Basin, there is a set of northeast-trending sub-basins (Exmouth, Barrow, Dampier, Beagle, Dixon and Investigator, Kangaroo Trough, Exmouth Plateau Arch, and Rankin Platform) that contain thick Mesozoic and Cainozoic sequences above Palaeozoic sediments to a maximum thickness of about 15km (Hocking *et al.* 1987). Faults trend northeasterly and easterly.

The structural evolution of the Carnarvon Basin occurred in three stages: Silurian to Late Permian; Late Permian to Cretaceous; and Late Cretaceous to present day. Sedimentation began in the Silurian (Tumblagooda Sandstone, Dirk Hartog Formation, Kopke Sandstone) with tectonic activity causing uplift of the Pilbara Block. Initially, the Carnarvon Basin was an interior-fracture basin formed by Late Ordovician-Early Silurian rifting (Hocking *et al.* 1987), towards the end of the Silurian a fall in sea level and a period of quiescence resulted in shallow marine to tidal flat conditions (Sweeney Mia Formation). Following a period of non-deposition during the Early Devonian, marine conditions were again established over the area. Devonian sediments were deposited mainly across a shallow marine shelf and an interior-sag basin developed (Nannyarra Sandstone, Gneudna Formation, Munabia Sandstone, Willaraddie Formation). Marine conditions continued into the Carboniferous with the deposition of the Moogooree Limestone, Quail, Williambury and Yindagindy Formations. Deposition was terminated towards the end of the Carboniferous with a major tectonic episode uplifting much of the basin and the adjacent Pilbara Block leading to the development of the Mesozoic sub-basins. Glacial conditions dominated the Late Carboniferous and Early Permian (Harris Sandstone, Lyons Group, Carrandibby and Callytharra Formations, Cordalia and Moogooloo Sandstones, Billidee Formation, Byro Group and Kennedy Group).

Subsidence and faulting related to the breakup of Gondwana began in the Late Permian and the Chinty Formation was deposited. A major marine transgression in the Early Triassic resulted in the deposition of the thick claystones of the Locker Shale. Regression began in the Middle Triassic with widespread fluvial and deltaic deposition occurring across the Exmouth, Barrow and Dampier Sub-basins as well as the Peedamullah Shelf. The thick sandstones of the Mungaroo Formation were laid down at this time. Deposition commenced in a shallow marine environment shallowing to marginal marine to paralic marine and eventually a fluvial environment.

Considerable tectonic activity took place during the Late- to Mid-Jurassic resulting in thick marine deposition in the restricted rifted basins of the Barrow-Dampier region to the west of the Peedamullah Shelf. Only minor sedimentation occurred in the Jurassic on the adjacent shelf regions, which were mostly uplifted and eroded, and the Exmouth Sub-basin (e.g. Dingo Claystone, Learmonth Formation). Breakup occurred at the end of the Middle Jurassic.

A marine transgression in the Late Cretaceous deposited the Winning Group, however ocean water circulation was still restricted. As transgression continued, increasing water depth resulted in further sediment deposition. The sandstones and silts of the Mardie Greensand Formation grade upward into the dark grey claystones of the Muderong Shale deposited under low energy open marine conditions.

From the Late Cretaceous to the present day, ocean water circulation was no longer restricted as the breakup of Gondwana was complete. Pelagic conditions existed over the basin. Conformably overlying the Muderong Shale is the Windalia Radiolarite, which in turn is overlain by the Gearle Siltstone, a low energy offshore marine deposit. Unconformably overlying the Gearle Siltstone are Tertiary sediments of the Cardabia Group and Trealla Limestone as well as undifferentiated surficial alluvium.

3.2. MAJOR LANDFORM ASSOCIATIONS

At all scales the structure and formation of landforms is tied to the geology of the inner continental shelf, particularly the width of the shelf, nearshore reef systems and the presence of islands and gulfs. The bedrock outcrops of the nearshore waters and coast comprise a geologic framework consisting of a series of Pleistocene limestone features and older sedimentary rocks of marine and terrestrial origin which outcrop as islands, approximately shore-parallel reefs, rock platforms and cliffs. Alongshore variability of the shelf structure of the Gascoyne coast is described for each secondary compartment in Appendix E, with vulnerability assessment classification at this scale in Table 5-1, Table 5-3 and Table 5-5. The alongshore variability of the reef structure of the primary cells adjacent to the Areas of Planning Interest is described per cell in Appendix G, along with cell vulnerability assessment classifications. The shelf and reef structure is demonstrated visually in Figure 1-1, in the Department of Transport and Australian Navy navigation charts, Geoscience Australia bathymetry and survey records presented by Brooke *et al*. (2009).

3.2.1. Nearshore Morphology: Reefs, Sand Banks and Sub-tidal Terraces

The Gascoyne coast is in a transitional zone for metocean processes, influenced by mid-latitude through to tropical synoptic systems, and transitioning from diurnal to semi-diurnal tides. Its landforms are mainly controlled by the geology, inherited deltaic features and the contemporary supply of sediment. The coast varies from a narrow shelf coast south of Shark Bay, the gulf coasts of Shark Bay and Exmouth Gulf, the deeper shoreface between Point Quobba and Gnaraloo, and the shallow coral reefs and lagoons that are common from Alison Point to the North West Cape. In addition, rivers and streams are significant in the Gascoyne coast. Most of the river mouths are wave dominated and barred (Wright 1985; Digby *et al.* 1998; Heap *et al*. 2001), particularly the Murchison River at Kalbarri and the many ephemeral streams and creeks of the Trealla and Range Land Systems around Alison Point and Cape Range, respectively. An exception is the Gascoyne River delta at Carnarvon which is an active river dominated deltaic system. Inherited deltaic features are associated with the Wooramel River, Gascoyne River (Johnson 1974; Hocking 1990), the river systems draining into Lake MacLeod and the Yannarie River. The sediment supply in many areas is dependent on erosion and reworking of sediments from these inherited features, together with contemporary sediment sources. The largest unconsolidated sedimentary landforms, sub-tidal and intertidal terraces, are predominantly located along the sheltered shores of Shark Bay and the eastern shore of Exmouth Gulf. Other accretionary landforms, such as the cuspate foreland at Winderabandi are located in the lee of fringing coral reef along the Ningaloo coast. Conversely, extensive erosional forms, such as large cliffs and extensive platforms are more prevalent along the exposed sections of coast where the inshore bathymetry is deep, as along the Zuytdorp Cliffs and in the vicinity of Cape Cuvier.

The influence of changing metocean conditions on coastal sheltering provides an over-riding control on coastal landform change. Hence, the influence of reef structure on inshore metocean processes is included in the assessment of vulnerability through the *Nearshore Morphology* category for Susceptibility and *Inshore Substrate* category for Instability (Table 2-6). The proximity of rock to the coast and its surface structure (width, depth, roughness and gaps) modify the local metocean processes in the lee of reefs and islands (Silvester & Hsu 1993; Mc Ninch 2004). Along the Gascoyne coast, particularly between Point Quobba and North West Cape, water level, waves and currents interact with outcrops of coastal limestone and coral reef to modify the inshore processes, including sediment transport and water circulation patterns (Sanderson & Eliot 1996). *Nearshore Morphology* classes the highest susceptibility rate for coastlines without reef and the lowest susceptibility for a continuous offshore reef, a shallow lagoon or a shallow shelf (platform, terrace or bank). The three rankings in between incorporate concepts of varying reef continuity and structure. *Inshore Substrate* classes the most unstable inshore areas as those without any rock outcropping and the most stable as those with almost continuous rock cover or hard rock that has a high resistance to erosion.

Sediment availability and transport, and therefore the stability of the coast, is partially affected by the nature of the inshore substrate, the presence and width of a sub-tidal or inter-tidal terrace and the presence and behaviour of salt flats and tidal creeks (Section 4.3.7).

<u>Sub-tidal terraces</u> can provide a buffer to sheltered coasts from changes in metocean forcing or extreme events, through reworking of sediments and adjustment of terrace width and depth, if there is sufficient capacity for the necessary provision or loss of sediment. The

presence of a terrace is included in the assessment of vulnerability through the *Shoreface Structure* category for Susceptibility (Table 2-6). The least susceptible shoreface has a wide terrace (>250m), with susceptibility increasing to a ranking of 2 as the terrace narrows. The nominal distance of 250m has been used for this assessment, although the effectiveness of the terrace to act as a buffer may reduce for wider inter-tidal areas. A sandy shoreface without a terrace or tidal flat is considered the most susceptible sandy shoreface structure.

The morphology of the inshore substrate is included in the assessment of vulnerability largely through the *Inshore Substrate* category for Instability (Table 2-6). A hard rock substrate close to the surface of the seabed is unlikely to store much available sediment and is therefore the most stable. However, sediment is likely to be transported across such surfaces. Conversely bare sand surfaces are unstable and commonly show evidence of active transport, such as sand ripples. The most unstable *Inshore Substrate* category of bare sand may also correspond to the situation of a terrace.

Sediment availability in areas of tidal flats is also affected by the width of the tidal flat (*Shoreface Structure* category for Susceptibility) and features of the shoreline (*Tidal Flats-shoreline features* category for Instability) and surge zone (*Tidal Flats-landward features* category for Instability) that affect sediment redistribution. Such features include vegetation cover, presence and continuity of cheniers, and presence and development of tidal creeks.

3.2.2. The Shore: Structure, Shoreline Shape and Orientation, Beaches and Rocky Coasts

Land systems along the shore include rocky coast topography, barrier systems, deltas and the frontal dune complex comprising the foredunes and frontal dunes. Their susceptibility to metocean change is dependent on shoreface structure, sediment supply, shoreline shape and orientation, beach type, river mouth or delta type and presence of rock (Table 2-6). Their instability is a function of their current condition and related to the type of beach and frontal dune characteristics.

Gulf coasts and Islands are two further types of coastal system within the Gascoyne coast, in addition to Cliffs, Deltas and Barriers. Islands are not discussed within the present framework. Gulf coasts are complex. They include the presence of tidal flats and sheltered shores with sediment accumulation forms. Gulf coasts are incorporated in the present assessment of vulnerability through the exposure and aspect of the coast (*Shoreline Shape & Orientation* category for Susceptibility the accumulation forms at the coast and tidal flats. The accumulation forms are accounted for in the *Shoreface Structure* and *Barrier* categories for Susceptibility. Sheltered gulf coasts can have the presence of a sub-tidal or inter-tidal terrace, which is included in the *Shoreface Structure* category for Susceptibility. The presence of a terrace reduces the susceptibility. The flats and banks associated with previously active deltas are assessed as relatively susceptible in the inherited deltaic features *Barrier, Deltas or Other Structure* category for Susceptibility. Supratidal accumulation landforms such as forelands, spits, cheniers and barriers are represented in the *Barrier* category for Susceptibility as relatively susceptible. Tidal flats are incorporated in the assessment for vulnerability through the *Shoreface Structure* category for Susceptibility, *Tidal Flats-shoreline features* and *Tidal Flats-landward features* categories for Instability.

Coastal orientation, or the direction to seaward the coast faces, determines the prevailing and dominant metocean processes to which it is susceptible. In the present analysis coastal orientation is included in the assessment of vulnerability through the *Shoreline Shape & Orientation* (particularly orientation) category for Susceptibility (Table 2-6). It is considered in relation to the exposure to major storms on the open coast and/or the prevailing conditions in sheltered gulf environments. For the open coast, the *Shoreline Orientation* has the highest susceptibility ranking for cells facing west and lowest susceptibility for cells facing south. However, this is a classification of the aspect of the majority of the sediment cell or compartment, and neglects localised variability within a cell. Additionally, large shifts in aspect generally coincide with coastal compartment boundaries. Orientation rankings included in Table 2-6 are not applicable to the sheltered environments of Shark Bay and Exmouth Gulf. A subjective susceptibility ranking for *Shoreline Orientation* has been applied for the three secondary compartments and two sediment cells considered within Exmouth Gulf. A different ranking system would be required for where the direction of prevailing metocean forcing changes, such as the Pilbara and Kimberley coasts.

Susceptibility of the barrier and shoreline shape increases with reduced geological control. This has been included in the assessment of vulnerability through the *Shoreline Shape & Orientation* (particularly shape) and *Barrier* categories for Susceptibility (Table 2-6). Cuspate forelands and tombolos have the highest susceptibility of any shoreline shape, followed by salients. Conversely, the least susceptible shoreline configuration is a straight, uninterrupted coast; however, this can be the most unstable. The vulnerability ranking for a cell may not account for the cuspate foreland or salient as these landforms are often located on the cell boundaries and do not represent the majority of the shoreline configuration within the cell. Each cuspate foreland or tombolo should be considered separately to the adjacent cells as it will often be more vulnerable to future environmental change.

Several different types of beach are recognised in the literature including sheltered and estuarine beaches (Nordstrom 1992; Jackson *et al.* 2002), exposed, wave-dominated beaches (Wright & Short 1984; Short 2005) and perched beaches. Beach stability has been included in the assessment of vulnerability through the *Beachface Morphology and Profile* category for Instability (Table 2-6). Instability rankings for these types have been ordered according to the degree of wave exposure, with the most unstable beaches exposed to the highest wave energy. The most stable profile is the case of where there is no beach (rocky shore) or sheltered beaches (with flat or segmented profiles). The sheltered beaches are often associated with a sub-tidal terrace, which is incorporated in the *Shoreface Structure* category for Susceptibility.

Perched beaches are common features of the Gascoyne coast, as they are for much of the shore of the Central and Mid-West coasts. Such beaches are not widely described in the literature (Green 2008; Doucette 2009) although they are highly significant features and occur along long reaches of coast in the Gascoyne region. Perched beaches are comprised of unconsolidated lenses of sandy or coarser marine sediments overlying or perched on sub-tidal to supratidal bedrock surfaces.

Perched beaches are included in the assessment of vulnerability largely though the *Beachface Morphology & Profile* category for Instability (Table 2-6; Figure 2-11), with considerations of susceptibility linked to cliffed coasts (*Shoreface Structure* and *Barrier* categories). The stability of a perched beach is determined by the elevation of the underlying rock structure in relation to water levels. The perched beaches least vulnerable to environmental change are those where the rock elevation is above high tide and the least stable are perched on a shallow pavement. However, perched beaches can occur on a smaller spatial scale than the sediment cell and should be considered in any local assessment.

Perched beaches are also a common feature of cliffed coasts, including those with cliff top dunes. Cliffed coasts are included in the assessment of vulnerability through the *Shoreface Structure category* for Susceptibility, with perched dunes considered in the *Barrier* category (Table 2-6; Figure 2-8). The susceptibility of the shoreface on a cliffed coast is related to the height of the cliff or bluff and the presence or absence of an intertidal platform (*Shoreface Structure*). The least susceptible rocky coast is a high cliffed coast that plunges to sub-tidal level, without any inter-tidal platform. The most susceptible rocky coast is gently sloping. Similarly, the least susceptible perched dune is located on supratidal or higher rock surfaces, with susceptibility increasing as the rock elevation decreases (*Barrier*).

Extensive tidal flats occur within Shark Bay and Exmouth Gulf. Tidal flats are included in the assessment for vulnerability through the *Shoreface Structure* category for Susceptibility, *Tidal Flats-shoreline features* and *Tidal Flats-landward features* categories for Instability. The vulnerability of a tidal flat is relevant to mean sea level changes of less than one metre and how that will influence the sediment supply and availability. A tidal flat is a susceptible structure with susceptibility decreasing with terrace width as there is a larger area to respond to changes in water level. This is demonstrated in the rankings of 4 and 5 in the *Shoreface Structure* category for Susceptibility.

Features of the shoreline affecting sediment redistribution on the tidal flats, and hence coastal stability, are incorporated in the *Tidal Flats-shoreline features* category for Instability. It is recognised that for many of these features there is a threshold above which stability may be significantly reduced. However, for the purpose of this assessment, the stability has been evaluated considering present-day environmental conditions. The most stable tidal flat is one where there is a continuous lithified chenier ridge. Instability increases with the number of tidal creeks and discontinuities in cheniers connecting the surge and the sub-tidal zones. This is due to an increase in the number of locations potentially oscillating between acting as a source or sink of sediment. The least stable tidal flat is a bare tidal flat with connection between terrestrial surface run-off and tidal channels.

Some features of the surge zone, the supratidal area subject to marine inundation during extreme storm or high sea level events, affect the sediment redistribution on the tidal flats and hence coastal stability. These are incorporated in the *Tidal Flats-landward features* category for Instability. The vegetation cover, width of the salt flats and number of tidal creeks are the three variables considered. The most stable coast has a well vegetated surge zone with a high cover of Halophytic plants and narrow salt flats. The stability decreases as the number of tidal creeks increases, vegetation cover decreases and salt flat width increases due to a greater capacity for sediment movement. The least stable tidal flat is unvegetated broad salt flats with numerous tidal creeks linked to fluvial processes and terrestrial flooding.

A distinction is drawn between tidal creeks in different locations and with different functions. For example, tidal creeks along the Wooramel Bank are different in form and function to those along the Yannarie salt flats on the eastern shore of Exmouth Gulf. The former are driven by tidal currents operating on the sub-tidal terrace. The latter include tidal flows in channels which appear to have originated as, and are primarily maintained by surface drainage during floodwater discharge.

3.2.3. Onshore Landforms: Barriers, Dunes and River Deltas

Formation of a barrier is a response to large-scale, long-term processes associated with changes in sea level sweeping the inner continental shelf during a rise in sea level over the Holocene, peaking at approximately 6,000 years ago. The coastal response to this large scale change in sea level is continuing at present. Rogers (1996) recognised three phases of barrier development from the Mid-West coast of WA and this may apply to areas of the Gascoyne coast. The phases are likely to be related to inter-decadal fluctuations in storminess, sea level and the wave regime, as well as pulsational sediment supply along the coast as well as an intermittent supply from the rivers. Such low-frequency changes are difficult to determine from the comparatively short, available historical records of coastal change although they may be apparent in the stratigraphic record.

Processes underlying barrier formation and the diversity of landforms associated with them have been widely discussed; for example see reviews by Roy *et al.* (1994), Hesp & Short (1999a) and Masetti *et al.* (2008). In a seaward sequence the main barrier features match those of a retrograding coastal sand barrier comprising active and inactive parabolic dunes and/or foredune ridges as well as the beach and shoreface as described by Cowell & Thom (1994) and Hesp & Short (1999a).

The susceptibility of barriers to change is a function of barrier type and size. Following the nomenclature of Roy *et al.* (1994), the largest and least susceptible to change are episodic transgressive barriers which have undergone phases of dune activity leading to development of a dune ridge through the formation of foredunes, blowouts and nested parabolic sand dunes as the ridge migrates landwards. The most susceptible to change due to metocean forcing are mainland barriers where a thin wedge of sand abuts rocky coast. However, there are differences between the Australian East and West Coasts. The principal distinction is that dunes forming the WA barriers commonly overlie the coastal limestone and therefore are comparatively less susceptible to change due to metocean forcing. Hence Roy *et al.* (1994)'s model has been combined with the degree to which the barrier system is affected by the geological framework to determine its susceptibility to change through the *Barrier, Deltas or Other Structure* category for Susceptibility (Table 2-6; Figure 2-10). In the Study Area the barriers least susceptible to extensive erosion are either large episodic transgressive barriers or barriers perched on high rock surfaces (Figure 2-10). The most susceptible to change are mainland beaches fronting cliffs or bluffs or unconsolidated spits and cheniers.

The stability of barriers and dunes is included through the *Frontal Dune Complex* and *Barrier Vegetation Cover* categories for Instability (Table 2-6; Figure 2-13). Under extreme onshore wind conditions barriers migrate landwards. The proportion of vegetation cover on the barrier, as a whole, is an indication of its surface stability. Similarly, vegetation cover on the foredunes and frontal dunes is also an indication of their stability. Additionally, scarping of the foredunes and frontal dunes is evidence of shoreline movement and possibly erosion. Hence, the degree to which a foredune is developed or the seaward margin of the frontal dune is cliffed provides an indication of the stability of the frontal dune complex.

Rivers are associated with mobile landforms and modify the supply of sediment to the coast. The rivers and creeks of the Gascoyne coast have experienced varied activity over time, including evidence of avulsion for river dominated deltas. Rivers switch from being a sediment source during flood events, to potentially acting as sediment sinks for intervening periods. In general, the rivers of the Gascoyne coast have been significant contributors of terrestrial sediment to sections of the coast, with ongoing reworking of those sediments. For example sediments from the Gascoyne River have contributed to the formation of the foredune plain between the river mouth and Point Quobba (Hocking 1990).

The deltas most susceptible to environmental change are as those which are river dominated. This is acknowledged in the *Barrier, Deltas or Other Structure* category for Susceptibility (Table 2-6; Figure 2-9) with the rankings allocated as a result of the episodic river systems of the Gascoyne coast having virtually zero base-flow. The river and wave-dominated deltas may alternately trap or release sediment at the coast, with some mouth structures more susceptible. During significant runoff flooding, sediment may be released from deltaic features, including the bar, beach and inshore areas; in the path of the river flow. In addition sediment can also be supplied to the coastal system from the banks and bed of the alluvial channel, from flooded alluvial or estuarine flats and from the catchment. After a scour event, the scoured channel and inshore area will act as a sink, trapping sediment until the bar has reformed, then becoming a feature that can be bypassed by alongshore sediment transport. While the bar is acting as a trap, it can potentially starve the downdrift coast until the bar is reformed and fully bypassing. The river mouths could potentially act as sediment sink for decades following a significant flood event.

Most susceptible to change are deltas with active stream channels, a high sediment supply, historical mobility of alluvial landforms and potential for avulsion. The Gascoyne River delta at Carnarvon is an active deltaic system, with avulsion of the river mouth occurring over time (Johnson 1974; Hocking 1990). The inherited deltaic features associated with reduced river activity or avulsion is the second most susceptible river type. The Wooramel River and Yannarie Creek were previously more active deltas. There is ongoing reworking of sediments between southern Shark Bay to Point Quobba due to the inherited deltaic features of the Wooramel and Gascoyne Rivers, with historic influence of the marine transgression of Lake MacLeod, in addition to the Eastern Exmouth Gulf associated with Yannarie Creek.

4. Coastal Processes

This section documents the available information on metocean forcing and some of the key factors which should be considered in further site-specific coastal processes investigations.

Coastal processes are active over all time scales simultaneously. Care is required to ensure the process of change is not inappropriately identified due to confined use of one or two concepts of change (refer to Section 4.5). Hence the hierarchy of geomorphic features, from landscape elements to mega-landforms and based upon spatial and temporal variability (Figure 2-7) has been used as an aid to identify active processes likely to determine the stability of the Gascoyne coast.

The metocean forcing is reviewed using wind, tropical cyclone track, water level, wave, rainfall and discharge datasets (Figure 4-1). The variability and influence of these processes are described at a regional scale in Section 4.2 with local scale influences on sediment transport in Section 4.3 and local measurements in Section 4.4.

- Meteorologic conditions contributing to the wind, wave and nearshore current regimes have been considered from stations at Kalbarri, Carnarvon, Denham, and Learmonth (approximately 35 km south of Exmouth) (Table 4-8). Particular reference is made to extreme weather events likely to generate storm surge or significant eolian transport of sediment;
- Tropical cyclone tracks from the Bureau of Meteorology;
- Tides and surges are described from water level records from Carnarvon and Exmouth (Table 4-9). Some details are included on shorter water level records for Denham, within the Ningaloo reef area and within Exmouth Gulf.
- Descriptions of offshore wave conditions have been derived from a directional waverider buoy record off Exmouth (2006-present; Table 4-12).
- Hydrologic information has been included for the Murchison, Wooramel and Gascoyne rivers using rainfall and discharge datasets. Further information is included on the ephemeral creeks and streams, including the example of Exmouth.

The specific information used has been detailed in each section.

4.1. IDENTIFYING KEY METOCEAN PROCESSES

Coastal and landform instability may result from a range or combination of multiple processes, over differing time and spatial scales (Komar & Enfield 1987; de Vriend *et al*. 1993; Masetti *et al*. 2008). The sensitivity to different processes varies between landforms, such that consideration of a limited set of processes may yield highly variable performance when projecting possible change. Consequently, it is necessary to consider a full range of active processes and identify those which most significantly influence the landforms of interest. Such an evaluation may need to consider how processes may interact. An example is provided by dune development, which requires coincidence of sediment supply, onshore winds and vegetation growth (Hesp & Short 1999b).

Figure 4-1: Monitoring Stations
Locations of current datasets are described in Section 4.4.4

The National Committee on Coastal and Ocean Engineering (NCCOE 2004) has suggested climate change assessment should be undertaken using a sensitivity framework to reduce the likelihood that poorly understood or modelled processes are neglected (NCCOE 2004; Abuodha & Woodroffe 2006). The framework suggests examining the sensitivity of the existing system to a suite of possible mechanisms, listed according to environmental (K1-K6) and process (S1-S13) variables (Table 4-1). By identifying the processes which are large amplitude or frequent, and to which the local system is most responsive, the focus for management may be highlighted.

It is noted that the aspect being evaluated (coastal and landform stability) includes the secondary variable foreshore stability (S9), which has therefore been neglected. Other parameters of ocean currents/ temperatures (K2), air temperature (K6), effects on structures (S5), estuary hydraulics (S11), quality of coastal waters (S12) and ecology (S13) have been neglected due to their limited relevance to the site.

Table 4-1: Primary and Secondary Coastal Variables (NCCOE 2004)

Primary Variables	Secondary Variables		
K1 – Mean Sea Level	S1 – Local Sea Level	S8 – Beach Response	
K2 – Ocean Currents/ Temperatures	S2 – Local Currents	S9 – Foreshore Stability	
	S3 – Local Winds	S10 – Sediment Transport	
K3 – Wind Climate	S4 – Local Waves	S11 – Hydraulics of Estuaries	
K4 – Wave Climate	S5 – Effects on Structures	S12 – Quality of Coastal Waters	
K5 – Rainfall / Runoff	S6 – Groundwater	S13 – Ecology	
K6 – Air Temperature	S7 – Coastal Flooding		= Limited Relevance

The Gascoyne coast is in a transitional zone for metocean processes, influenced by mid-latitude through to tropical synoptic systems, and transitioning from diurnal to semi-diurnal tides. Within the Gascoyne coast, the structure and formation of landform units (sub-tidal terraces, beaches, dunes, tidal flats, deltas and coastal barriers) are strongly tied to the geology (presence and formation of nearshore reef systems, rock outcrops at the shoreline, the topography of the inner continental shelf), inherited deltaic features and the contemporary supply of sediment.

The over-riding control on coastal landform change is the influence of coastal sheltering combined with changing environmental conditions (Box 4-1), and therefore an assessment of inner shelf, nearshore reef structure, terrace and tidal flats have been applied as primary indicators of coastal sensitivity.

The structure and relative dominance of each of the inner shelf, gulf/bay structure, islands, nearshore reefs and outcrops of rock at the shoreline delineates the coastal landforms according to the eight primary compartments of the Study Area (Table 2-1; Figure 1-3 to Figure 1-5; bathymetry shown in Figure 1-1; following approach by Searle & Semeniuk (1985). Each primary compartment experiences different metocean forcing at a regional scale due to the inner shelf influence, aspect and sheltering (Section 4.3.1) and at a local scale through further modification to processes by the varied nearshore and inshore geologic structure (Section 4.3.2-4.3.4).

In addition to the coastal sensitivity caused by shelf structure, reef sheltering or exposure, there is considerable further variation within the sequence of landform units progressing shoreward (Table 4-2). The examples of a sandy coast are included in Table 4-2.

Box 4-1: Inner Shelf Structure, Nearshore Sheltering, Geologic Control and Terraces

The inner shelf structure, nearshore reef and islands systems, underlying geology and the presence of sub-tidal terraces and tidal flats influence the Gascoyne coastal processes.

The inner shelf structure can modify incident wave energy and influence the susceptibility to storm surge events. The inner shelf structure can reduce some of the incident wave energy, largely as a result of refraction, with some influence of wave breaking and diffraction across northern Shark Bay and northern Exmouth Gulf. The main delineation in the inner shelf structure is identifiable at the primary compartment scale, with the two more exposed compartments (Freycinet and MacLeod) having a narrower and deeper inner shelf, and the more sheltered and shallower compartments located within Shark Bay and Exmouth Gulf. Currents and waves generated by local winds are important in these compartments.

The reefs and associated lagoons of Ningaloo Reef (Allison Point to North West Cape) further provide varied sheltering of the adjacent coast. The degree of shelter is largely dependent on the surface structure of the reef, including the degree of reef continuity and depths, along with the offshore distance of the reef structures (Sanderson & Eliot 1996). Complex swell diffraction and refraction patterns through the discontinuous reef system and around islands, is superimposed on wind- and tide-driven circulation in the lagoons, locally generated wind waves and transport offshore through gaps in the reef (Sanderson 2000).

Outcrops of coastal limestone and sandstone at the coast can occur in the form of cliffs, headlands, platforms, ramps and beachrock outcrops. The beaches and landforms in proximity to this coastal limestone are geologically controlled, with the interaction between the local metocean processes, available sediment and underlying rock structure governing the beach response.

Potential response of the Gascoyne coast to future changes in water level and wave climate, including direction, will not be uniform due to the varied inner shelf, nearshore reef and island and structures, rock outcrops at the coast and tidal flat and terrace structures (Semeniuk 1996b); and may include landform migration and retreat.

For this study, the relative importance of different processes has been considered with respect to eight landform unit components described in Section 2.4. In general terms, there is a progression in time scales from rapid response at the beach scale, through to gradual, slow change for the barrier system as a whole (de Vriend *et al*. 1993; Cowell & Thom 1994).

This general and simplified sensitivity assessment has been developed by Damara WA on the basis of geology and geomorphology in the region, and does not represent a comprehensive analysis of the coast.

When defining development constraints and opportunities, it is essential that planners and foreshore managers comprehend and make allowance for the combined effects of geomorphic evolution, natural climate fluctuations, greenhouse-induced climate change and other anthropogenic changes that may affect foreshores, including active coastal management, or land use change. In many cases, it is pressures introduced by multiple sources of change that create ongoing management issues.

The frequency of coastal flooding, tidal cycles, inter-annual sea level fluctuations and vertical land movements must be considered when evaluating relative change in sea level. Increases in mean sea level due to El Nino / La Nina phase, plus 4.4-year and 19-year tidal cycles influence the number of coastal flooding events, which may not directly relate to greenhouse-induced climate change (Pattiaratchi & Eliot 2008; Eliot 2011).

Table 4-2: Sensitivity of Landform Units to Environmental Parameters

Zone Parameter	Beach	Foredune	Primary Dune	Barrier System
K1 – Mean Sea Level	High	High	Medium	Low
K3 – Wind Climate	Low	Medium	High	Medium
K4 – Wave Climate	High	Medium	Low	Low
K5 – Rainfall / Runoff	N/A	Medium	Medium	Low
S1 – Local Sea Level	High	High	Medium	Low
S2 – Local Currents	Medium	Low	N/A	N/A
S3 – Local Winds	Low	High	High	Medium
S4 – Local Waves	High	Medium	Low	Low
S6 – Groundwater	Medium	Low	Medium	Medium
S7 – Coastal Flooding	High	Medium	Medium	Low
S8 – Beach Response	High	Medium	Low	Low
S9 – Foreshore Stability	High	High	High	Medium
S10 – Sediment Transport	High	High	Medium	Low

4.2. REGIONAL SCALE

The Gascoyne coast is located approximately between latitudes 21°47’S and 27°42’S on the west-facing coast of Australia, including Shark Bay and western Exmouth Gulf. It is a transitional zone for metocean processes, influenced by mid-latitude through to tropical synoptic systems and transitioning from diurnal to semi-diurnal tides. There are further regional variations due to the influence of the inner shelf and gulf structures at a primary compartment scale.

4.2.1. Meteorology

The climate of the Gascoyne coast reflects its location between the tropical low-pressure belt and the sub-tropical high pressure belt, with its northern limit at the boundary between the Temperate and Tropical Coast Regions. The region experiences a semi-arid to arid climate, with hot summers and mild winters. The seasonal cycle is occasional influenced by tropical cyclones and tropical lows, both of which have greater incidence towards the north (Gentilli 1971; Bureau of Meteology: BoM 1998). Rainfall is highly irregular, mainly distributed between two seasons from May to July and January to March, reflecting the relative influence of mid-latitude and tropical systems respectively. A regional summary of the climate in the Gascoyne is provided in *Gascoyne-Murchison Climatic Survey* (BoM 1998) and summarised below.

4.2.1.1. Weather systems

Regionally, weather is affected by the latitudinal shift of the sub-tropical high pressure belt, in combination with the summer continental heat trough (Gentilli 1971), with superposition of individual synoptic systems and the localised coastal influence of the seabreeze. Land and sea breezes produce prevailing coastal winds in the region and provide winds of moderate strength. Consequently, they are recognised to play a significant role in ambient environmental forcing (Pattiaratchi *et al.* 1997; BoM 1998). Sea breeze formation has rapid onset, initial velocities that are relatively high and nearshore surface currents that respond almost instantaneously.

During winter, the Gascoyne is dominated by high-pressure systems, promoting weak easterly winds and dry conditions (BoM 1998). As synoptic conditions are generally weak, the winds are modulated by the land-sea breeze cycle, with south to southwesterly seabreezes. The prevailing high pressure ridge is interrupted by fronts and pre-frontal troughs, associated with mid-latitude low pressure systems to the south of the Study Area. These may produce strong winds and rainfall (Figure 4-2). The frequency and intensity of mid-latitude systems decreases with distance north, although fronts associated with them may link with sub-tropical systems (BoM 1998). Strong winds may be generated from any direction during winter. Winter rainfall mainly occurs from May to July generated by cold fronts and cut-off lows, with extreme winter rainfall potentially occurring if northwest cloud bands connect to mid-latitude depressions.

During summer, there is a southward migration of the convergence of the trade and monsoon winds resulting in tropical lows and occasional tropical cyclones inpinging on the Gascoyne region (BoM 1998), with occasional strong local winds generated by thunderstorms. Sea breezes are the prevailing winds during this period. They may be stronger in summer in areas of the Gascoyne due to the co-alignment of thermal and geostrophic winds. This generally results in prevailing southerly winds, switching from southeasterly in the morning to south to southwesterly in the afternoons. The intensity and direction of the sea breeze is influenced by the coastline orientation and topography, surface friction and synoptic pressure patterns, including the location of the approximately north-south aligned trough (Figure 4-3; Pattiaratchi *et al.* 1997; BoM 1998). The summer sea breeze pattern may be suppressed when the trough is located offshore or during the influence of tropical systems. Notable variations to the general south to southwesterly seabreeze occur in the complex coastlines of Shark Bay and Exmouth Gulf and in the lee of Cape Range (Section 4.4.1).

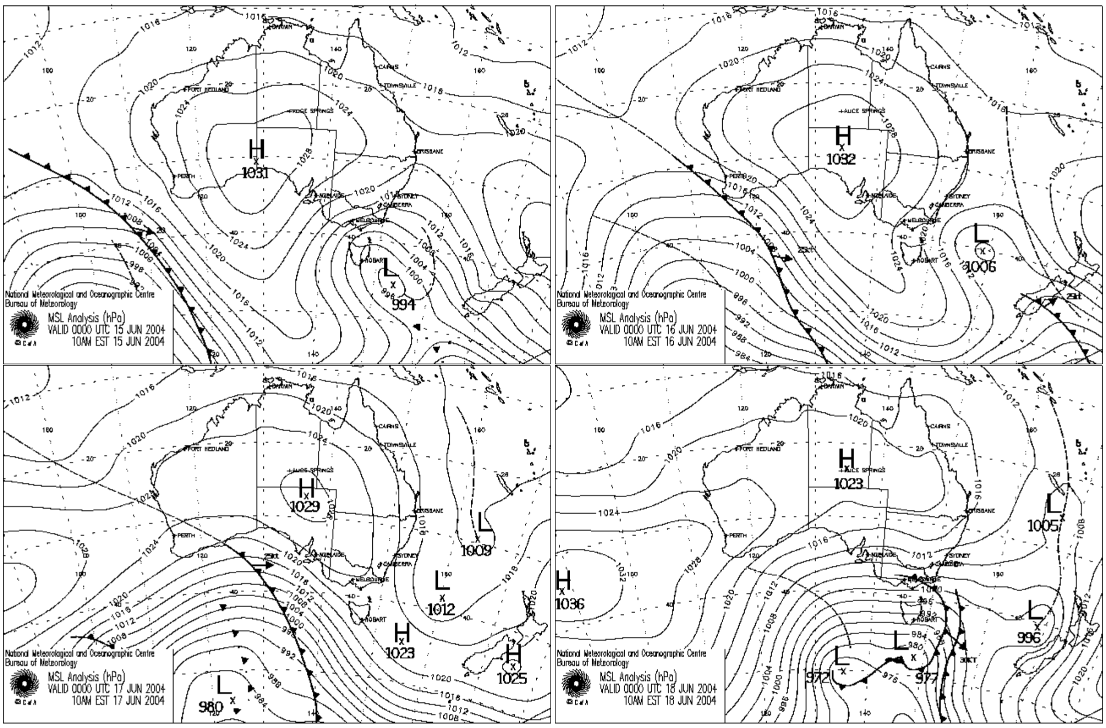


Figure 4-2: Example of Common Winter Synoptic Conditions

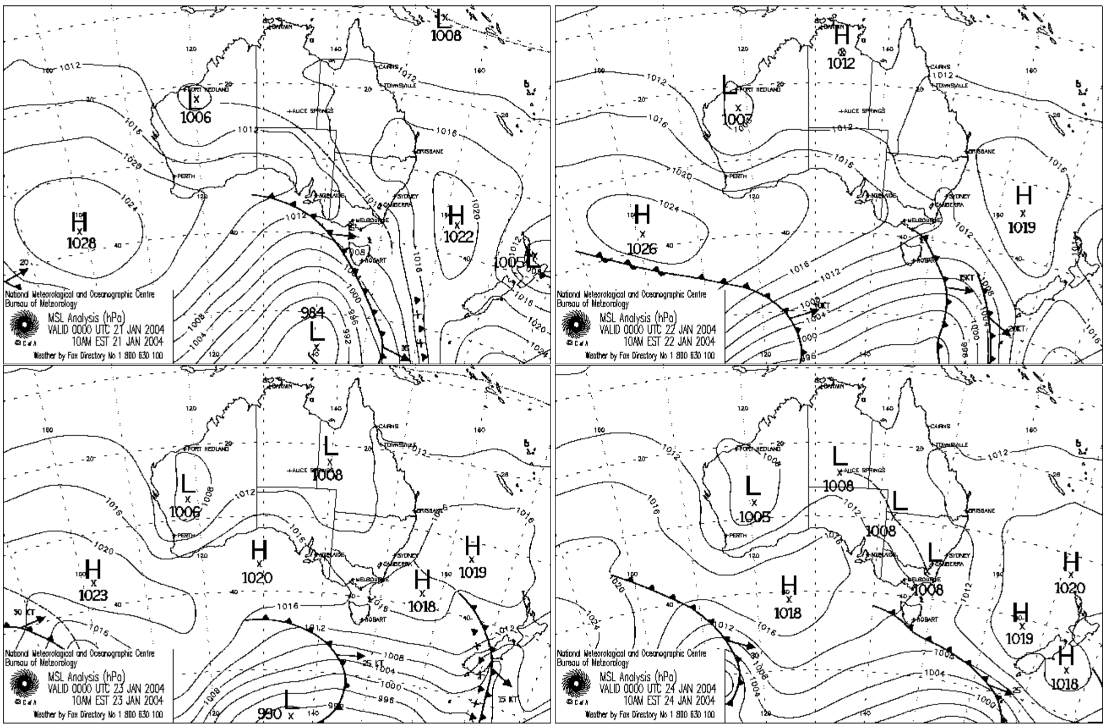


Figure 4-3: Example of Common Summer Synoptic Conditions

An important synoptic feature in the warmer months is a low pressure heat trough, sometimes producing thunderstorms and modulating the sea breeze (Figure 4-3; BoM 1998). Gradient intensification can occur when any low pressure front or trough interacts with adjacent higher pressure systems (Steedman & Russell 1986). Fluctuations in the intensity and location of the heat trough, as well as diurnal and local topographic influences affect day-to-day variations in wind direction and speed from the general land-sea breeze system. Prevailing wind conditions may be disturbed for several weeks during the passage and aftermath of tropical cyclones, or for longer periods associated with destabilisation of the heat trough, albeit with much milder influence.

Summer rainfall generated by tropical lows and thunderstorms mainly occurs from January to March, with highly variable contribution from tropical cyclones.

The average wind speed, direction, duration, extremes and event frequency for the main weather systems experienced on the Gascoyne coast is listed in Table 4-3. Deviations in the strength and direction of winds with distance north in the Study Area occur due to interaction between weather systems. An example of the interaction is the stronger seabreeze in summer due to the co-alignment of thermal and geostrophic winds.

Table 4-3: Main Local Weather Systems

Weather System	**Anticyclones (High Pressure Ridge)**	**Thunderstorms (Heat troughs & convection)**	**Fronts, troughs, gradient intensification & Interaction to N**	**Tropical Cyclones & Tropical Lows**	**NW Cloudbands**	**Sea Breezes**
Occurrence	Annual	Dec-Mar	May – Aug	Dec– Apr	Apr – Sept Strongest May-Jun	All year. Strongest Oct – Mar
Average Wind Speed	Light	-	15-29 m/s	Up to 50 m/s	-	10 m/s
Average Duration	Unknown	1-3 hours (longer if associated with a low)	10-55 hours	12-24 hours	1-4 days	~7 hours
Average Wind Direction	All	-	N to NW to W to SW; Or if track to south NE to SW to SE	Depends on path	-	190-225° (Exmouth also has N-NE)
Frequency	3-10 days	25% of significant rain events. 1-30/year.	1-3 / year, frequency decreases to the north	1 in 3 years. Aignificant events 1 in 10 years	10/year	Almost daily
References	Gentilli 1972; BoM 1998	BoM 1998	Gentilli 1971, 1972; BoM 1998	Damara WA 2008; BoM 1998	BoM 1998; Wright 1997	Pattiaratchi *et al.* 1997; BoM 1998

4.2.1.2. Storm events

Weather systems and their interactions may generate conditions of strong winds, surge and rainfall. These dominant conditions modify sediment supply and transport patterns, result in storm erosion, potentially modify unstable landforms and can generate terrestrial and coastal flooding. The dominant conditions are associated with the following weather systems, with significant spatial, seasonal and interannual variability (Steedman & Russell 1986; BoM 1998; GEMS 2000; Damara WA 2008; Eliot 2010):

- Winds
    - Tropical cyclones

    - Thunderstorms
    - Seabreezes in summer with co-alignment of thermal and geostrophic winds
    - Fronts interacting with weather systems to the north
- Surge
    - Extreme onshore wind events, which occur when tropical cyclones cross south to the south of North West Cape or cross west to the east of North West Cape
    - Tropical cyclones travelling parallel to the coast resulting in shelf waves
- Rainfall
    - Tropical depressions including tropical cyclones, tropical lows and associated thunderstorms are the dominant summer rain systems
    - Northwest cloudbands, particularly connected to mid-latitude depressions are the dominant winter rain systems
    - Cold fronts with higher frequencies further south
    - Troughs and lows. Thunderstorm-producing heat troughs occur in warmer months and cut off lows are more common in autumn and winter.

Mid-latitude winter storm events are a frequent phenomena affecting the western coast of Australia (BoM 1998) but their influence reduces northwards due to increasing distance from the synoptic systems' centres. In counterpoint, there is a general increase in the influence of high pressure systems towards the extra-tropical ridge, which migrates seasonally across the Gascoyne region. In consequence, the Gascoyne coast and inland river catchments typically experience slightly milder winter storms than the southwest with increased effect from high pressure system interactions, including pre-frontal troughs and gradient intensifications (generally longitudinal). Winds developed by both high and low pressure systems interact with thermal gradients, including trade winds, cold fronts and coastal land-sea breeze cells.

The clockwise rotation of mid-latitude depressions produces onshore winds, which may deliver low to moderate rainfall (Figure 4-2). High winter rainfall across the Gascoyne region may be possible when the synoptic system connects with a moist tropical air mass, producing a northwest cloudband sequence. Rainfall may be further enhanced during a northwest cloudband if the low-pressure air mass detaches from the mid-latitude trough, forming a cut-off low (BoM 1998).

Northwest cloudbands are a cloud mass forming off the northwest coast and extending southeast towards the land. Their formation is due to lifting of moist tropical air by cold air intruding north, associated with a strong mid-latitude trough or cold front. Northwest cloudbands are the primary cloud system that produces rainfall in the cooler months of the year from April to September, most frequently in May and June. The percentage of winter rainfall produced by cloudbands increases with distance north through the Study Area (Wright 1997; BoM 1998).

Thunderstorms are common inland of the coast. They may deliver short bursts of rainfall to catchments, causing flash flooding, and extreme winds at the coast. Thunderstorms are produced in the warmer months through heat-driven convection and are generally associated with the heat trough, tropical lows and tropical cyclones. They may also occur in winter when they are associated with deep low pressure systems. Most thunderstorms last for a few hours with some organising into longer-lasting severe storms with strong wind gusts, intense rainfall and possibly tornadoes.

The tropical cyclone season affecting Western Australia occurs from November through to April with up to 10 tropical cyclones during one season (Damara WA 2008). Direct impact of cyclones along the Gascoyne coast is less frequent occurring on average, once every two to three years (Damara WA 2008), with a significant impact once every 10 years. The frequency of direct impact increases with distance north (Eliot & Pattiaratchi 2010). Peak frequencies of tropical cyclones are recorded in the Pilbara between Karratha and Onslow, adjacent to the northern reaches of the Exmouth Gulf (Damara WA 2008). Tropical cyclones can cause extensive damage as a result of strong winds and flooding, associated with either heavy rainfall or ocean storm surges (BoM 1998; Eliot & Pattiaratchi 2010). The intensity of tropical cyclones is such that direct impact, even by a relatively weak cyclone, commonly causes “highest recorded” levels of wind, wave height and water level (Damara WA 2008).

The Bureau of Meteorology holds a database of recorded tropical cyclone events from as early as 1907, which follows from early summaries by Coleman (1972) and Lourensz (1981). This database includes, by definition, all tropical depressions for which gale force winds were observed (above 63 km/hr). The central zone of low pressure defines the location of tropical cyclones. However, the frequency of tropical cyclones prior to the 1970’s is likely to be underestimated, given the relatively poor capacity to analyse weather systems before the advent of radar and satellite technology (Lourensz 1981).

Analysis of the tropical cyclone database has previously been undertaken by Damara WA, for the purpose of characterising cyclone climatology. Information presented here has previously largely been presented in Damara WA (2008, 2009). Different types of tropical cyclones will generate separately the highest surge, winds and waves or river flows in the Gascoyne (Figure 4-4; Figure 4-5).

The highest **surge** is associated with either tropical cyclones tracking parallel to the coast (shelf waves, eg. TC Bianca in 2011 and TC Glynis in 1970) or those which cross the coast to the south of the site (barometric surge, wind and wave set-up, (eg. TC Vance in 1999; Damara WA 2006b; Figure 4-4). The relatively largely west facing shore of the Gascoyne coast, excluding Shark Bay and Exmouth Gulf, reduce the significance of tropical cyclone induced surges compared to the North-West (Damara WA 2008). Hubbert *et al*. (1991) reported that TC Hazel in 1979 developed a higher surge at Carnarvon by travelling coast parallel than an equivalent system would have produced approaching coast normal.

Tropical cyclones may produce strong **winds and waves** in any direction due to their intense radial structure. They commonly pass southwards offshore, and hence produce northeast winds, swinging through to northwest, westerly and southwest winds (Damara WA 2008). Tropical cyclones also commonly change to a south-southeasterly path north of the Study Area, tracking towards the coast and modifying wind directions from easterlies prior to land crossing and westerlies subsequently (Gentilli 1971).

High **river flows** are largely associated with tropical cyclones that recurve towards the southeast across the Pilbara causing heavy rainfall on the river/creek catchments. For example TC Vance in 1999 at Exmouth and in the Gascoyne (Figure 4-5A and B), TC Emma in the Murchison (Figure 4-5C) and TC Katie in 1964 causing 412.8mm rainfall in one day at Yardie Creek near Exmouth (BoM 1998). The most significant flooding occurs once a catchment is already saturated, with sequential events such as occurred in 1960 and 1961 for the Gascoyne River generating widespread flooding (Table 4-17; BoM 1998).

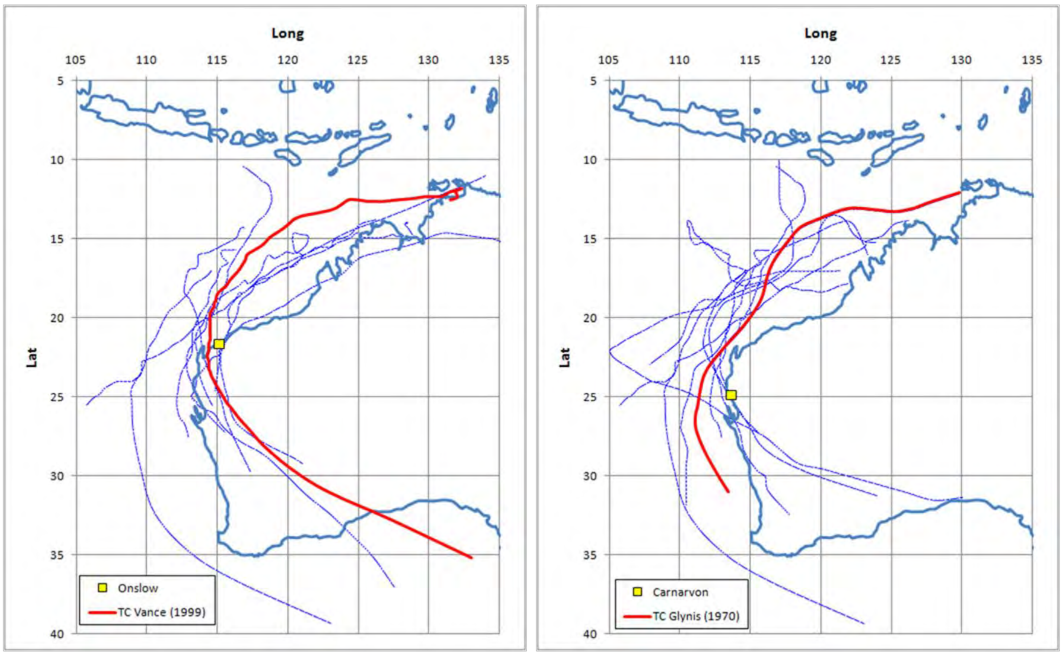


Figure 4-4: Tropical Cyclone Paths Causing Greatest Surge (A) Onslow (1966-2008) and (B) Carnarvon (1966-2008) (Source: Damara WA 2008)

4.2.2. Water Levels

Water level processes experience a significant transition across the Gascoyne region, with major changes for both tidal and non-tidal phenomena. Key changes are caused by the range and distribution of weather systems, variation of continental shelf structure, change in coastal aspect and influences of embayment structure.

Along the Western Australian coast, tides vary from micro-tidal, mainly diurnal tides in the southwest through to macro-tidal, mainly semi-diurnal tides across the Northwest Shelf. The Gascoyne region experiences mixed tides, with an approximate balance between semi-diurnal and diurnal forcing (National Tidal Facility 2000). Due to this rough balance, the local tidal form is ultimately determined the influence of factors which modulate tide, such as shelf and embayment structure, where the water body is resonant with a particular cycle, or where frictional effects cause tidal currents to slow or focus (Damara WA 2008). These effects enable relatively rapid geographic variation of tidal form, including a switch in tidal form between the two gulfs in Shark Bay, and on either side of Exmouth Peninsula. Tidal forcing contains a range of cycles, including the semi-diurnal ranging, the monthly spring-neap cycle, bi-annual cycles of diurnal and semi-diurnal tides due to movement of the solar equator, a 4.4 year cycle developed from lunar elliptic motion and a 19.6 year cycle developed from lunar nodal modulation (Damara WA 2008; Eliot 2010).

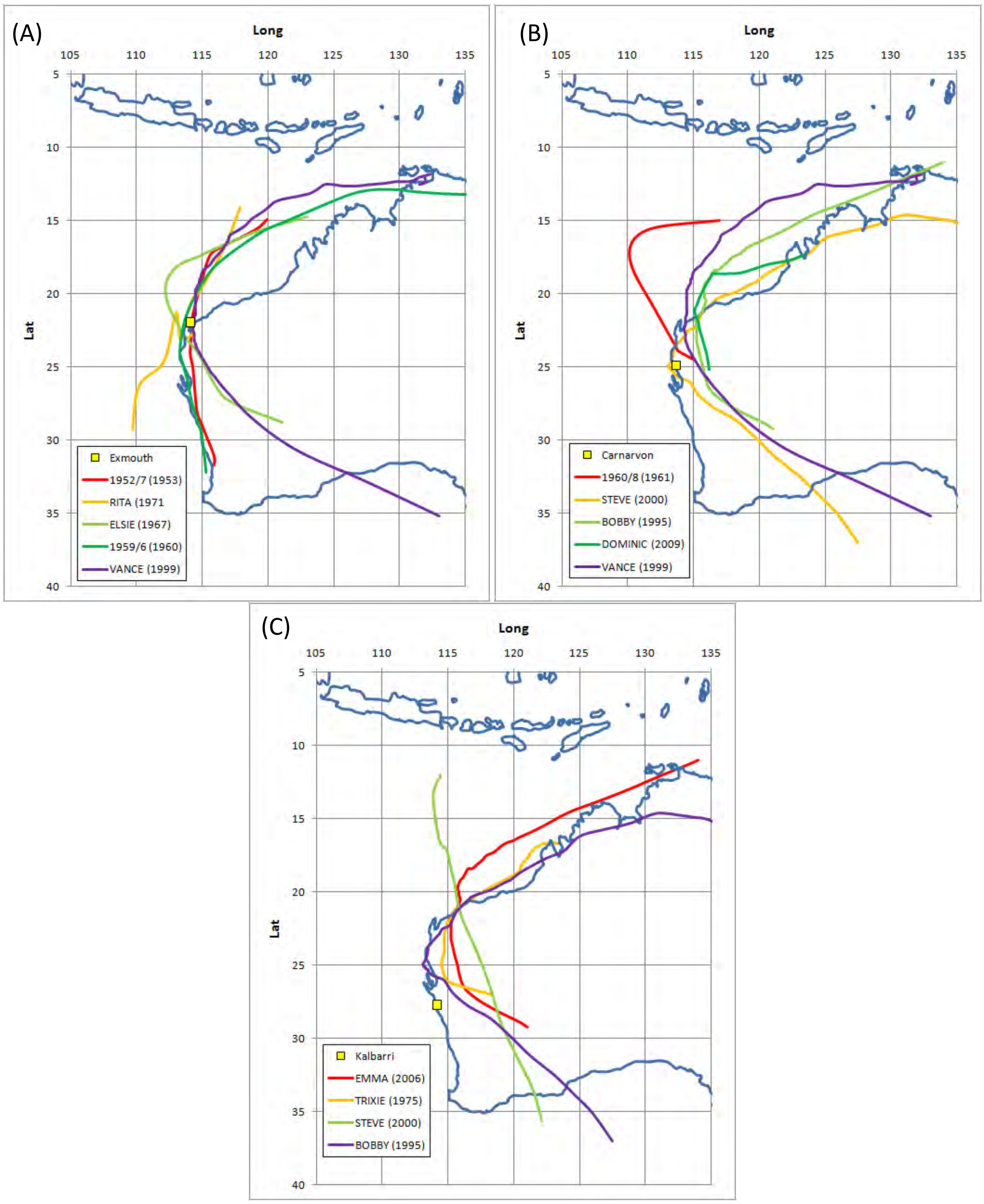


Figure 4-5: Tropical Cyclone Paths Causing Some of the Greatest Rainfall Events (A) Learmonth; (B) Gascoyne River and (C) Murchison River

The bathymetric structure, aspect and gulf shoreline structure configuration also modify the influence of non-tidal water level processes, including storm surges and resonant phenomena. Surge is mainly attributed to mid-latitude depressions and tropical systems, with infrequent tropical systems providing the dominant surge signal. Surge may be enhanced by bathymetric features including transitions from deep water to wide and shallow shelf; or funnelling into convergent gulfs or embayments (Gönnert *et al*. 2001). Offshore reef chains or an irregular coastline may reduce the effects of wind setup (Damara

WA 2006b). Bathymetric effects on tide, surge and resonant phenomena is described in Section 4.3.1.

Process information has been derived from the sustained water level measuring station at Carnarvon (1966 to present with gaps in 1976-1977, 1982-1984 and 1986-1989), with the second longest record at Exmouth (1989-1993 and 1997-present) and a number of shorter tide gauge deployments throughout the Gascoyne region. Water level processes are described for the Gascoyne coast by a summary of previous dataset analyses (National Tidal Facility 2000; Damara WA 2008; Eliot 2010). The water level climate has a distinctly tidal character with perturbations from mean sea level variations and surge events.

Mean sea level variations are largely attributed to changes in the strength of the Leeuwin Current and movement of regional atmospheric pressure belts.

The seasonal variations of tides, surges and mean sea level are generally not in phase (Table 4-4; Damara WA 2008; Eliot 2010):

- Both the diurnal and semi-diurnal constituents vary bi-annually, with solstitial peaks in June and December for the diurnal constituents, and equinoctial peaks in March and September for the semi-diurnal constituents. Within the Gascoyne region, for sites with mixed tides, tidal peaks may be obscured through the effects of inter-annual tidal modulations;
- Surge peaks due to tropical cyclones mainly occur in January to March, with mid-latitude storm systems causing surges from June to August ;
- The seasonal mean sea level peaks during April at the north of the Study Area and peaks in May to June further south.

This relative timing may restrict may restrict the potential for high water levels to a relatively narrow time frame (Damara WA 2008). The timing of high water levels is such that they are generally coincident with a portion of the cyclone season for the coast north of Carnarvon and out of phase southwards from Geraldton.

Table 4-4: Peaks in Water Level Components
(Source: Damara WA 2008)

Location	Tide Peaks	Surge Peaks	MSL Peaks	Peak
Onslow	Mar, Sep	Dec-Apr	Apr	Feb-Apr
Carnarvon	Mixed	Jul-Aug	Apr-May	Any
Geraldton	Jun, Dec	May-Jun	May-Jun	May-Jun

Peak water levels recorded at tide gauges are likely to be underestimates of extreme cyclonic water levels. Observed tide gauge levels can be lower due to the sheltered position of the tide gauge, damping due to the gauge stilling well and the discrete nature (in time and space) of the gauge (Damara WA 2010). Debris lines can provide a site-specific measure of the limit of surge combined with wave runup (Nott & Hubert 2005).

4.2.2.1. *Tsunami*

Tectonic activity along the southern margin of the Indonesian archipelago has provided an active source of earthquakes and volcanic eruptions capable of generating tsunami that affect Western Australia, including the Gascoyne coast. There is a modern record of moderate tsunami activity for Western Australia, with palaeotsunami evidence suggesting larger events have occurred. The majority of evidence is interpretive in nature (Bryant & Nott 2001; Nott & Bryant 2003) but suggests that at least two large tsunami have occurred, around 350-400 years ago and 900 years ago (Damara WA 2010). Along the Gascoyne coast, boulder deposits, possibly caused by tsunami have been identified at Point Quobba, along the northern Ningaloo coast and North West Cape (Bryant & Nott 2003; Nott 2004; Simpson *et al.* 2007). Deposits at North West Cape are located up to 2-15m above mean sea level, suggesting extreme pre-historic tsunami or surge events.

Modern observations of tsunami across and near the Gascoyne region have included:

- March 2005, July 2006 and September 2007 (Pattiaratchi & Wijeratne 2009) – The 2006 tsunami resulted in localised runup of approximately 8m at Steep Point, south of Shark Bay (Commonwealth of Australia 2010);
- 2004 Boxing Day – observed along the WA coast with a maximum wave height of 1.14m at Carnarvon (Pattiaratchi & Eliot 2008; Pattiaratchi & Wijeratne 2009);
- June 1994 – propagating to 3-4m above sea level at North West Cape and in Exmouth Gulf (Nott 2004; Pattiaratchi & Wijeratne 2009). Anecdotal evidence of this event around the Cape Range area included inundation of ≈7m high dunes at Jurabi Point, potential inundation more severe in areas with gaps in Ningaloo Reef, transport of water 200-300m up Tantabiddy Creek and to the road near the Light House Caravan Park west of Vlamingh Head (Simpson et al. 2007);
- 1977 tsunami – possibly propagating to 6m above MSL near Cape Leveque, north of the Study Area (Dominey-Howes 2007) from a 2m wave (Bryant & Nott 2003);
- September 1937 – affected Onslow east of the Study Area (Simpson et al. 2007); and
- 1883 Krakatoa – water level fluctuations of over a metre at Carnarvon rising and falling three times in 1.5 hours (BoM 1998: 2) and over 3m at Geraldton (Bryant & Nott 2003), south of the Study Area.

Despite their relative rarity, the potential extreme scale of tsunami has prompted detailed hazard assessment and modelling (Legget 2006; Simpson *et al.* 2007; Burbidge *et al.* 2009; Geoscience Australia & Fire and Emergency Services Association 2010). Detailed modelling has been conducted for the Exmouth region, including collation of anecdotal and site evidence of the 1994 tsunami (Simpson *et al.* 2007).

Modelling of tsunami propagation along the southern arc of the Indonesian Archipelago has indicated that there are two locations within the Gascoyne area that are natural focal points for impact due to offshore bathymetry at the Exmouth Plateau and Wallabi Plateau (Leggett 2006; Geoscience Australia & Fire and Emergency Services Association 2010; Figure 4-6). The focal points occur due to bathmetry, tsunami propagation characteristics and any reflection off Indonesian islands. The two locations are: (1) from approximately False Entrance along the eastern side of Dirk Hartog Island, including Steep Point; and (2) from Yardie Creek in the

Cape Range National Park around to Exmouth, including Vlamingh Head and Exmouth. A third focal location occurs in the vicinity of Point Quobba.

In addition to the tsunami propagation and regional bathymetric effects, the landward movement of solitary waves generated as the tsunami 'breaks' in shallow water further determines tsunami impact. Coastal runup may be in the order of 10m above the tsunami level. The tsunami-generated waves respond similarly to ocean waves, and are affected by local bathymetry and topography, with potential focusing of energy through gaps in the reef, such as at Jurabi Point and Tantabiddi Creek (Simpson *et al.* 2007).

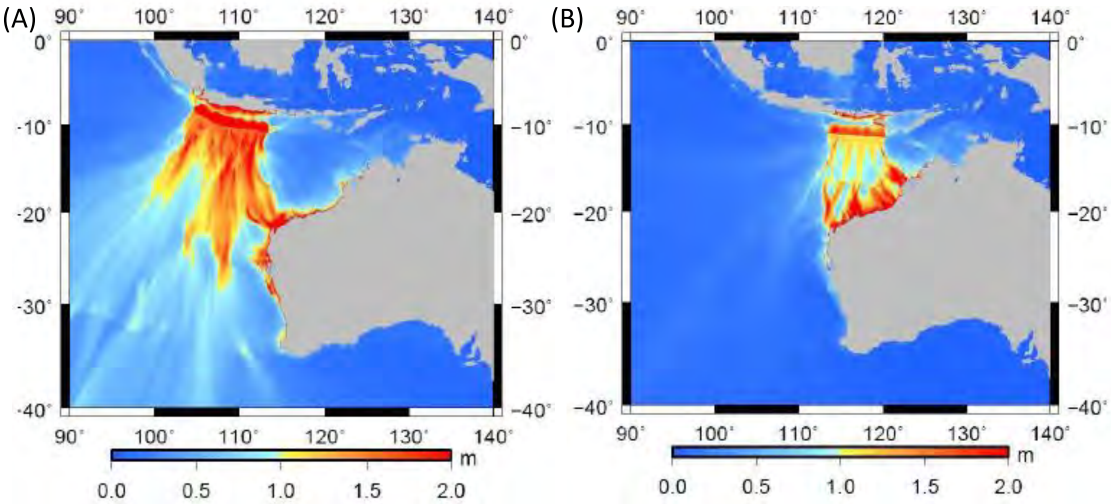


Figure 4-6: Modelled Tsunami Scenarios
(A) Magnitude 9.3 Earthquake off Java and (B) Magnitude 9.1 Earthquake off Sumba
(Source: Geoscience Australia & Fire and Emergency Services Association 2010)

Tsunami are a hazard as they can directly inundate an area, flatten dunes and be funnelled through any dune breaches, whether they be artificial breaches for access tracks, natural low points or associated with ephemeral creeks. Emergency planning, including possible signage, is required in areas potentially affected by tsunami (Commonwealth of Australia 2010).

4.2.3. Waves

The Gascoyne area experiences a range of weather systems from tropical to mid-latitude origin, with a corresponding variety of wave generation. This transitional character is further enhanced by the continental structure, with the change in coastal aspect at North West Cape and the shelter of Shark Bay and Exmouth Gulf providing significant changes in the origin of prevailing waves. Extreme waves throughout the region are largely associated with extreme onshore winds generated by tropical cyclones, although their frequency reduces significantly from the north-facing to west-facing coasts, as well as a reduction with increasing latitude.

Wave sources along the Gascoyne coast and their principal geographic zones of influence are:

- Southern and Indian Ocean swells, particularly south and west of North West Cape with limited influence in Shark Bay (Richardson *et al.* 2005).
- Winter easterly swell generated across the Timor Sea, particularly east of North West Cape with some refraction into Exmouth Gulf (Pearce *et al.* 2003; Metocean Engineers 2004).
- Locally generated wind waves during seabreezes and thunderstorms including fetch limited waves within Exmouth Gulf and Shark Bay; prevailing for Exmouth Gulf and Shark Bay (Steedman & Russell 1986); and
- Wind waves generated by infrequent tropical cyclones, which are dominant locally in combination with the associated surge.

Spatial variation of the swell wave climate is suggested by a wave hindcast from 1997 to 2002 (Figure 4-7; Li *et al.* 2008). The most significant variation in wave height occurs within Shark Bay, including the influence of Bernier and Dorre Islands and within Exmouth Gulf, including the influence of Muiron Islands, as a result of sheltering, aspect, depth effects and focusing of winds within the bay and gulf. There is a general decrease in wave heights towards shore due to depth effects, along with increasing shelter from reefs and islands.

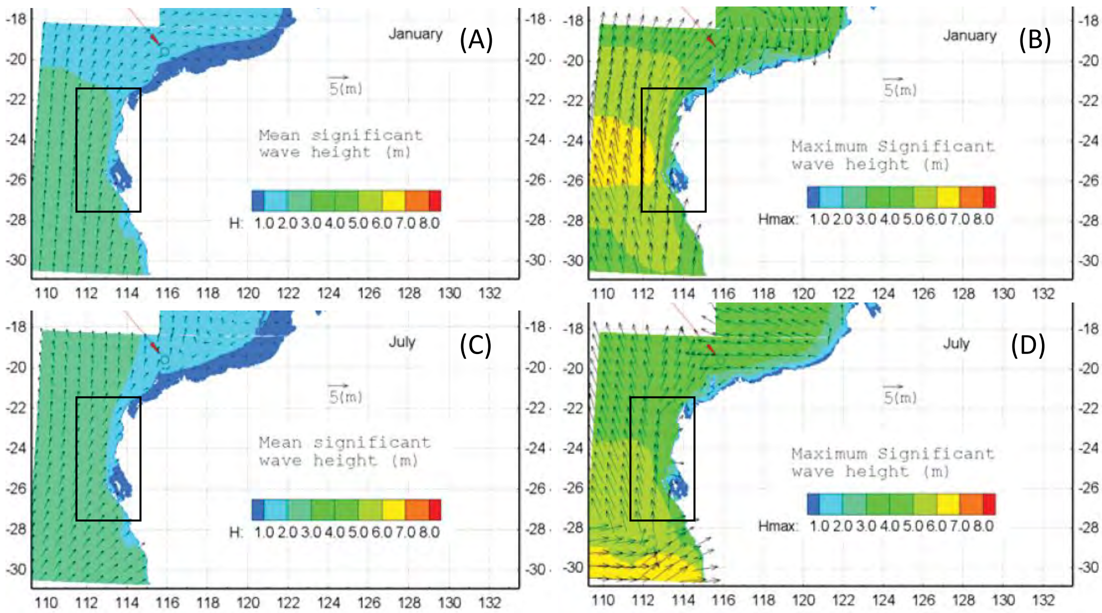


Figure 4-7: Indicative Variation of Significant Wave Heights Based on 1997-2002 CSIRO WAM Wave Hindcast
(A) Mean January, (B) Maximum January, (C) Mean July and (D) Maximum July
(After: Li *et al.* 2008)
Note: Study Area Shown in Black Box

The model results also show spatial and temporal variation in wave height occurring across the inner shelf in depths less than 50-100m, corresponding to the varied structure of the inner shelf of the primary compartments and the dominant wave source. The highest waves across January and July tend to occur in the offshore areas of the MacLeod Primary Compartment from Point Quobba to Alison Point. In July the maximum significant wave height tends to decrease with distance north across the Study Area due to reduced influence of the southern swells. In January, the maximum wave height decreases north and south of the MacLeod Primary Compartment due to the combination of swell events influence across the southern Study Area and tropical cyclones influencing the north.

The varied aspect, shelf, gulf/bay and reef structure of the coast, in the context of the transition in forcing mechanisms, restricts the ability to represent the Gascoyne area using individual datasets. In addition, it should be noted that numerical wave models tend to misrepresent locally generated wind waves, along with waves induced by tropical cyclones, partly attributed to limitations with the wind inputs (Jensen *et al.* 2006).

4.2.4. Currents/Circulation

The continental shelf offshore from the Gascoyne region can be described most simply by four different structures, with an open shelf for the southern and central parts of the coast, the broad semi-enclosed shallow Shark Bay, the narrow shelf with coastal fringing reef along Ningaloo and Exmouth Gulf. With the exception of regional off-shelf currents, these differences limit the geographic extent to which circulation measurements may be related. Consequently, the majority of available information regarding circulation in the Gascoyne region is relevant to regional offshore currents, measured at specific nearshore sites or generated using numerical models. The main sources of information have been collected for the Shark Bay and Ningaloo marine parks (Pearce & Pattiaratchi 1997; D'Adamo & Simpson 2001; Pattiaratchi 2008) and Exmouth Gulf (Heyward *et al.* 2006).

On the continental shelf, circulation may be driven by multiple processes, each of which may have greater or lesser influence under different bathymetric or synoptic conditions (Csanady 1997). In theory, four principal circulation drivers are oceanographic (steric gradients and weather systems), tidal, wind-driven (local winds) and wave driven processes. These have a general sequence of dominance moving seawards that relates to the relative influence of the forcing mechanisms (Figure 4-8; Damara WA 2010).

Regional currents have been examined using satellite imagery, drifters, gliders, boat based measurements, numerical models and long-term deployments of current meters at the Tantabiddy mooring on the Ningaloo coast (Hearn *et al.* 1986; Massel *et al*. 1997; Pearce & Pattiaratchi 1997; D'Adamo & Simpson 2001; Burling *et al.* 2003; Woo *et al.* 2006a; Heyward *et al.* 2006; Brinkman *et al.* 2007). These investigations provide a general focus on surface currents, the Leeuwin and Ningaloo Currents, circulation of Shark Bay and Exmouth Gulf and weather system forcing, including eddy formation and influences of islands.

In general, the boundary effect of the coast causes most surface currents in the nearshore to run nearly shore parallel. This pattern can be modified by the influence of reefs, islands and channels as discussed in Section 4.3.2 and density driven currents across the sills in Shark Bay (Burling *et al.* 2003). Further offshore the surface current direction becomes more responsive to the direction of forcing.

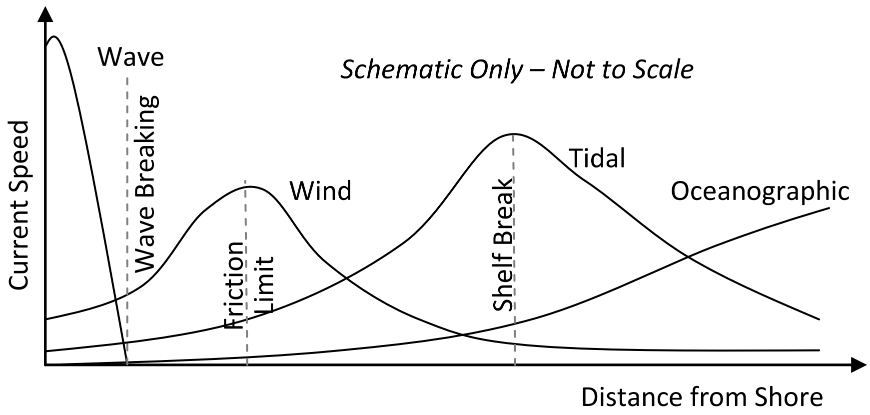


Figure 4-8: Schematic Spatial Distribution of Currents Excluding Density Driven Currents (Source: Damara WA 2010)

4.2.5. Hydrology

Rivers are significant for the planning of coastal areas due to their: direct roles of flooding and morphodynamics; ecological functions and indirect role of sediment storage or supply. It is the latter characteristic that provides the greatest influence of rivers on coastal landforms outside the immediate influence of the river systems. The behaviour is highly dependent upon the catchment structure and hydrology, but also varies in time, responding to catchment saturation and the significance of preceding floods, with a general sequence of sediment release during extreme floods and sediment capture during lower flows.

River and creek flood character and capacity for sediment delivery to the coast are affected by the catchment structure. Distinction can be made between the two ‘banjo-shaped’ catchments of the Murchison and Gascoyne rivers, to the ‘coastal’ catchments of the Minilya and Wooramel Rivers. The latter two rivers and many coastal creeks have low gradients, and correspondingly low stream power to provide sediment delivery. In contrast, there is high sediment delivery from the ‘banjo-shaped’ catchments of the Murchison and Gascoyne Rivers, which have relatively narrow coastal drainage paths and extensive upland areas separated by a topographic ridge. Although the coastal area generally receives higher rainfall, the upland area allows runoff concentration, with steeper stream gradients enhancing stream power (Figure 4-9).

Creek systems within the Gascoyne are often ephemeral, with locally significant incised channels draining ranges or escarpments in the Trealla Land System around Alison Point; Range Land System around Cape Range including Vlamingh Head and Exmouth; and on the peninsulas of Shark Bay. Flooding typically occurs during high rainfall events. The coastal catchment structure can be complex with fronting dune or bar breakouts and flood basins.

The wave or river dominance of the river mouth bar or delta also influence the flooding and erosion potential during flood events (Figure 2-9). Most of the river mouths of the Gascoyne coast are wave dominated (Wright 1985; Digby *et al.* 1998; Heap *et al*. 2001) and barred or fronted by dunes, limiting their capacity for sediment exchange, particularly the many ephemeral streams and creeks around Alison Point and Cape Range. The Murchison River at Kalbarri has greater capacity for exchange, but is still a wave-dominated delta. An exception is the Gascoyne River delta at Carnarvon, which is an active river-dominated deltaic system. Inherited deltaic features are associated with the Wooramel River, Gascoyne River (Johnson 1974; Hocking 1990), the river systems draining into Lake MacLeod and the Yannarie River. The sediment supply in many areas is dependent on erosion and reworking of sediments from these inherited features, together with contemporary sediment sources.

The influence of rivers and creeks varies along the Gascoyne coast in terms of flooding potential and influence on the sediment budget, and is considered a locally significant factor for the Areas of Planning Interest of Carnarvon, Miaboolya Beach, Vlamingh Head and Exmouth (Section 6). A regional assessment of the surface hydrology of the Murchison and Gascoyne regions was conducted in 1998 (Water & Rivers Commission: WRC 1998a). Flood studies and floodplain mapping have been revised recently for Carnarvon (SKM 2002) and Exmouth (SKM 2007) for revision of local structure plans and town planning schemes. The flood studies excluded the December 2010 flooding in Carnarvon due to a tropical low (BoM 2011) and included the March 1999 flooding in Exmouth due to Tropical Cyclone Vance (Martens *et al.* 2000; SKM 2007).

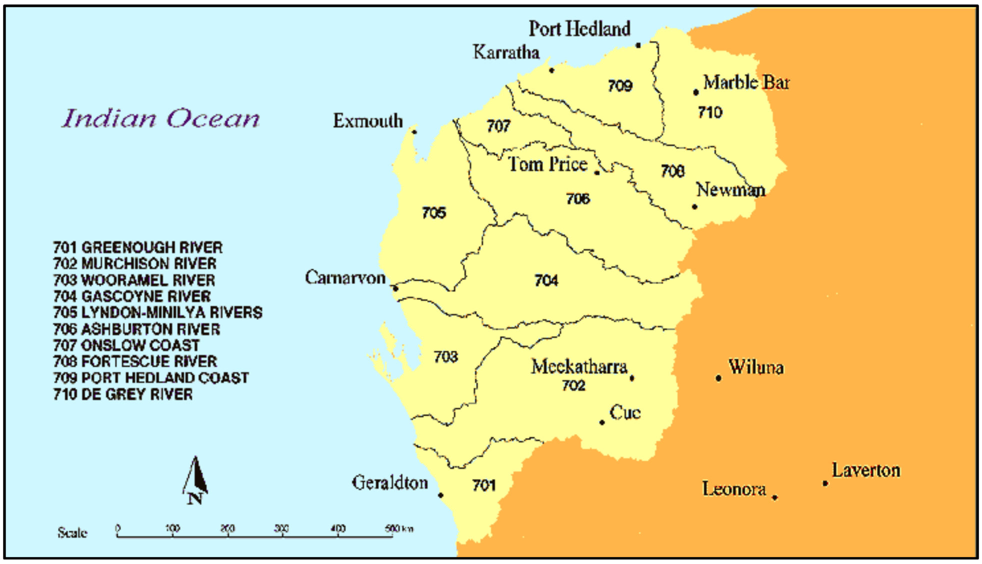


Figure 4-9: River Catchments
(Source: Department of Water)

The Gascoyne River has the highest potential river flow and provides the highest order of magnitude of terrestrial sediments to the coast, followed by the Murchison (Table 4-5; WRC 1998a). This is a significantly smaller contribution than the Fitzroy and Ord Rivers in northern Australia. The values presented in Table 4-5 are mean annual estimates with significant inter-annual fluctuations (BoM 1998; NLWRA 2001; Li *et al.* 2008).

The March 1999 flood in Exmouth illustrates the complexity of flooding of coastal catchments in the Gascoyne region. The six catchments through the townsite flooded during the passage of Tropical Cyclone Vance, with increased runoff due to the lack of vegetation in the catchments following a bushfire (Martens *et al.* 2000). The small coastal catchments, totalling 45 km^2, are fronted by coastal dunes that were formed by alongshore eolian transport and commonly result in deltaic deposition behind the dunes. Inundation of flood basins and dune breakouts can occur during a significant flood, with the location of breaching influenced by areas of historic breakouts, narrow dune width and human intervention. Artificial breaches in the dunes for beach access and any drainage or floodway diversions modify flood behaviour, which may change too rapidly to be captured adequately in flood studies.

Table 4-5: Major Rivers and Potential Sediment Supply
Rivers within the Study Area are Shaded
(Source: Li *et al.* 2008)

Sediment Source	Catchment Area (km^2)	River Flow (GL/y)	Suspended Sediment Export to the Coast (kT/y)	Mean Annual River Outflow at the Mouth Q (m^3/s)	Mean River Sediment Concentration C (kg/m^3)
Ord	85,213	9,448	600	300	0.063
Fitzroy	103,900	4,800	2,635	152	0.549
Gascoyne	78,548	1,117	Not Reported	35.4	0.023
Murchison	89,184	410	21	13	0.049
Greenough	12,568	44	28	1.4	0.63
Moore	13,540	396	21	12.7	0.05

4.3. LOCAL MODIFICATIONS

Meteorologic and oceanic drivers of coastal processes on the Gascoyne coast are described at a broad scale in Sections 4.2.1 through 4.2.5. However, the coastal response is a more complex function of the coastal morphodynamic system: which relates to the interaction of metocean forcing, the geological (sedimentological) framework and the landforms (Wright & Thom 1977). Interpretation of the landforms and geological structure may be used as a proxy to describe local scale variations in coastal processes that arise due to morphodynamic interactions.

4.3.1. Inner Shelf Structure and Coastal Aspect

Inner continental shelf structure and coastal aspect determine the prevailing and dominant metocean processes to which the coast is susceptible (Sections 3.2.1 and 3.2.2). The shelf bathymetry, nearshore bathymetry and coastal aspect may locally modify the wind-induced setup component of surge, currents and incident wave energy.

The wind-induced setup component of surge may be influenced by inner shelf bathymetry through its effect on currents induced by tropical cyclone wind stress (Jelesnianski 1978; Damara WA 2009). Surge is enhanced by bathymetric features that throttle cyclone induced currents including funnelling into convergent gulfs or embayments, or transitions from deep water to a wide and shallow shelf (Gönnert et al. 2001; Damara WA 2009). The effects of wind setup may be reduced by offshore reef chains or an irregular coastline that promote the dispersal of currents.

A wide and shallow shelf increases the potential surge and decreases the potential incident wave energy. The inner shelf structure can reduce some of the incident wave energy, largely as a result of refraction, with some influence of wave breaking and diffraction across northern Shark Bay and northern Exmouth Gulf (Figure 4-7).

Coastal aspect in the Gascoyne region is extensively controlled by the geologic framework. It is particularly complex in Shark Bay and Exmouth Gulf, but is also affected by the aspect and form of ridges and reefs on the inner continental shelf and close to shore, as well as inherited structures along the coast. Large shelf structures such as Shark Bay have had a long term influence on coastal landform development. Aspect is secondarily affected by the distribution of unconsolidated sediment that has accumulated against and over the bedrock topography during the Holocene, particularly the past 8,000 years, as a result of sea level rise and metocean processes (Section 4.3.7). It is the combination of the two geologic components, the rocky topography and unconsolidated sedimentary morphology that give the coast its present day form.

The main delineation in the inner shelf structure is identifiable at the primary compartment scale (Figure 1-2):

- Zuytdorp: The inner shelf is narrow and deep in the west-southwest facing cliffed coast from Kalbarri to Shark Bay. The significance of tides and surges are low due to the narrow shelf and coastal aspect, with a high exposure to Southern Indian Ocean swells (Figure 4-7).
- Shark Bay: The three compartments Freycinet, L'Haridon and Gascoyne are sheltered and shallow, located within the two reaches of the gulf coast of Shark Bay. Tidal resonance produces semi-diurnal dominance in one reach and diurnal dominance in the other (Burling *et al.* 2003). Occasional extreme surges have been associated both with direct cyclone impact and systems travelling largely coast parallel with associated shelf waves (GEMS 2009; Damara WA 2009). The shelf structure shelters the coast from incident swell increasing the dominance of locally generated wind waves and currents.
- MacLeod: The inner shelf is narrow and steep rising to cliffs and bluffs along the shorewith some reef sheltering, on the west to northwest-facing coast between Point Quobba and Gnaraloo. There s significant alongshore variability in susceptibility to surge, tropical cyclones and incident waves (Figure 4-7).
- Ningaloo: Shallow coral reefs and lagoons are common on the deep and narrow west-facing coast from Alison Point to the North West Cape. The west facing nature of the coast protects it against the majority of cyclones, as they produce offshore winds. However, the coastal response may be quite complex on a local scale, depending upon the reef structure (Hearn *et al.* 1986; Section 4.3.2).
- Exmouth Gulf: The two Exmouth Gulf compartments of Western Gulf and Eastern Gulf are sheltered and shallow. Tides and incident swell generally reduce towards the southern end of the Gulf, whilst there is some indication that surges increase southwards, particularly for cyclones running southwards along the west side of Cape Range (Steedman & Russell 1986; Damara WA 2009).

The coastal response to seasonal, interannual and interdecadal variability in winds, swell, water levels and currents will vary with coastal aspect and inner shelf structure. The variability of inner shelf structure and coastal aspect on spatial scales smaller than primary compartments should be considered in any coastal assessment.

4.3.2. Shoreface: Reef Structure

Three types of reef are apparent in the Gascoyne region (Section 3.2.1); living coral reefs, fossilised coral reefs and remnant limestone ridges. The older systems are referred to as limestone reefs in the context of this report. They comprise limestone pavements and platforms common in the region whereas the living reefs occur as fringing barrier reefs from Gnaraloo Bay to Point Murat where the Ningaloo Reef runs parallel with the coast for over 280 km (Hearn *et al.* 1986; Sanderson 2000).

Reefs are significant to sediment supply and for their effect on coast landforms. Ningaloo Reef is a relatively narrow fringing barrier coral reef with a large number of discontinuities along its extensive length (Hearn *et al.* 1986; Collins *et al.* 2003) with the reef providing an ongoing supply of sediment due to coral growth and bioproductivity. The reefs of Ningaloo create lagoonal structures in their lee with circulation affected by the gaps in the reef. In contrast to this, limestone reefs degrade over time and provide a declining supply of sediment through reworking of the carbonate sediments and lower rates of bioproductivity (Sanderson 2000). Both reef types may support perched sandy beaches with intertidal or supratidal rock platforms formed during periods of different mean sea level (van der Graaff *et al.* 1976; Collins *et al.* 2003; Twiggs & Collins 2010). The structure and formation of landforms along the shore is strongly tied to the presence of both types of reef systems in nearshore waters <20m deep (Sanderson & Eliot 1996; Sanderson 2000). The water level, waves and currents interact with the reefs to modify the inshore processes, including sediment transport at all time and space scales (Hearn *et al*. 1986; Taebi *et al*. 2011).

The degree of protection provided by broad reef systems is strongly affected by the wave conditions and the depth of water above the reef (Young 1989; Gourlay 1994; Brander *et al*. 2004). However, for narrow reef systems, significant further variability is associated with, wave spectral distribution, wave direction and reef structure (Hearn *et al*. 1986; Hearn 1999; GEMS 2005a; Lowe *et al*. 2009). Often the effectiveness of reef sheltering on the inshore wave climate is greater during lower water levels. Where the reef is emergent or partially emergent during low water conditions waves break at the outer edge and may possibly spill across the platform. Under high water conditions lower friction is experienced. A result of this variability is that storm erosion in many sections of the Gascoyne coast will be most significant when high water levels coincide with high wave energy events, as the wave energy will transmit across the reef (Hearn 1999; Damara WA 2003; GEMS 2005b). Potential future changes in amplitude and duration of water level fluctuations could alter the inshore wave climate and sediment transport, along with migration of secondary and tertiary sediment cell boundaries.

Reefs have influence on the inshore wave climate and landforms in several ways:

- Reduction of wave energy occurs through friction and wave-breaking which is dependent on reef structure, with an exponential decay in wave energy with increasing reef flat width (Fredsoe & Deigaard 1992). Greater wave energy can be transmitted during higher water levels. Local wind waves will consequently have more influence in areas where the reef protects the coast from incoming swell;
- Refraction and diffraction (due to islands or reef lumps) alters the wave direction;

- The discontinuous structure of the reefs creates variation in water level along the coast. Higher water levels will occur at gaps in the reef or lower reef sections, along with greater wave setup at the shore. This generates local circulation, with sediment transported away from the areas of highest wave transmission. It contributes to the presence of landforms characteristic of high sediment supply adjacent to gaps in the reef (Hearn *et al.* 1986; Sanderson 2000). The proportion of gaps along Ningaloo Reef was estimated at 15% by Hearn & Parker (1988) using aerial photography;
- In addition to diffraction of waves, reefs and islands have a wave shadow in their lee. This produces a relatively lower water level behind the island and may result in sediment deposition in the wave shadow area (Black 2003; Ranasinghe & Turner 2006); and
- The presence of rock also alters the sediment transport dynamics and sediment holding capacity of perched beaches (see Section 4.3.3).

Reefs and islands influence local sediment transport rates and pathways through their contribution to the formation and amplification of currents. Wave-generated rips are repeatedly developed in gaps through discontinuous reef sections, providing potential to transport sediment offshore (Hearn *et al.* 1986). Wind-driven flows and tidal currents can be focused through a constrained gap in the reef, or transferred to setup over a broad reef platform. Current amplification between reefs or islands and the land can result in locally enhanced alongshore sediment transport, contributing to the northward skewness of sedimentary accumulation landforms (e.g. cuspate forelands) on the Gascoyne coast (Sanderson 2000; Section 4.3.2.1).

Any local coastal processes investigations for the Gascoyne coast, particularly from Gnaraloo Bay to Point Murat, require consideration of reef influence on the inshore wave climate, currents and local patterns of sediment transport in response to reef and shelf variability. However, the relationships interpreted from short datasets are dependent on the monitoring period in relation to the natural variability of the wave, wind, water level and current climates and do not necessarily capture the full range of conditions occurring at the inshore sites. Care must be taken in the interpretation of available records, with further consideration that the potential response of the coast to future changes in water level and wave climate will not be uniform due to the various reef and lagoon structures.

4.3.2.1. Sedimentary Accumulation Features

Sedimentary accumulation forms include subtidal terraces, sills, spits, bay mouth bars, cuspate forelands and tombolos (Zenkovich 1967) as well as larger barriers (Roy *et al.* 1994, Brown 1988; Playford 1990) of which they form part. The varied development of the accrectionary landforms on the Gascoyne coast is attributed to the complex reef structure, the lagoon basin structure, the geologic framework, localised nearshore processes and sediment availability (Read 1974; Brown 1988; Sanderson & Eliot 1996; Sanderson 2000). Salients, cuspate forelands and tombolos are common along the Gascoyne coast in the lee of fringing coral reef between Gnaraloo Bay and Point Murat (Hearn *et al.* 1986; Sanderson & Eliot 1996) along the Ningaloo coast. Spits, embayments, sand banks, sills, sub-tidal terraces (Section 4.3.4), shell beaches and smaller accumulation features occur within Shark Bay (Logan & Cebulski 1970; Read 1974) and northwest Exmouth Gulf (Brown 1988; Leeden

2003). They are controlled by rock platforms, islands, headlands and tidal channels. Tidal flats are present on eastern Shark Bay and south and eastern Exmouth Gulf (Section 4.3.4).

Salients and cuspate forelands occur in the lee of different reef structures. Salients are low-amplitude, seawardly convex reaches of coast (Klein *et al.* 2002). However, cuspate forelands are promontories that project well seaward from the general trend of the shoreline, often at a point of convergence of waves and currents (Zenkovich 1967; Hsu & Evans 1989; Silvester & Hsu 1993; Hsu *et al.* 2008). In this report the larger features are commonly used to identify the boundaries of sediment cells in reef protected areas. Tombolos extend seaward to attach to an island or reef. The initial formation of these features largely occurred during periods of different mean sea levels within the Holocene (Sanderson & Eliot 1996), with extensive modification by contemporary metocean forcing. Salients, cuspate forelands and tombolos are included in the assessment of vulnerability for their susceptibility (Section 3.2.2) to changing metocean conditions. However, each cuspate foreland should be considered independently of the adjacent cells as each will often be more vulnerable to future environmental change.

There are extensive depositional landforms on the Ningaloo coast associated with the coral reefs (Sanderson 2000). Five types of sedimentary accumulation forms on the Ningaloo coast have been identified by Sanderson & Eliot (1996) and are shown schematically in Figure 4-10, together with their alongshore distribution. Many landforms are skewed in the prevailing wind direction with prevailing northerly longshore drift driven by wind conditions, and lagoonal currents driven by tides and wave set-up (Sanderson 2000). The accumulation features are further influenced by wind-driven circulation and local enhancement of currents between the landform and the reef or island (D'Adamo & Simpson 2001) as well as alongshore sediment transport by breaking wind waves, wind-driven currents and eolian transport.

The formation and migration of salients, cuspate forelands and tombolos is potentially reversible under changing metocean and sediment supply conditions (Zenkovich 1967). There may be a tipping point of landform erosion that results in rapid retreat that is likely to be irreversible across the planning timeframe of 100 years. This could occur as a result of a loss of reef control (e.g. partial collapse), as has occurred at Post Office Beach in South Australia (Fotheringham 2009) and/or a significant reduction in sediment supply from coral reef mortality or loss of sediment bioproduction in seagrass communities.

Spits occur on the Gascoyne coast, such as the Babbage Island spit at the entrance to the Carnarvon Fascine which is supplied with sediment from the Gascoyne River. Additionally there are numerous spits within Shark Bay. Spits and bars are highly dynamic and unstable features that are subject to modification through migration, breaching and overwash; all of which occur on a variety of time and space scales (Zenkovich 1967; Aubrey & Gaines Jr 1982). The processes of change to these landforms have important effects on the local coastal sediment budget. An important supply of sediment to the coast involves the migration and collapse of these landforms against the beachface, such as occurs at Denham, Monkey Mia and Shell Beach, closure of bay mouths and impoundment of small coastal lagoons such as Little Lagoon.

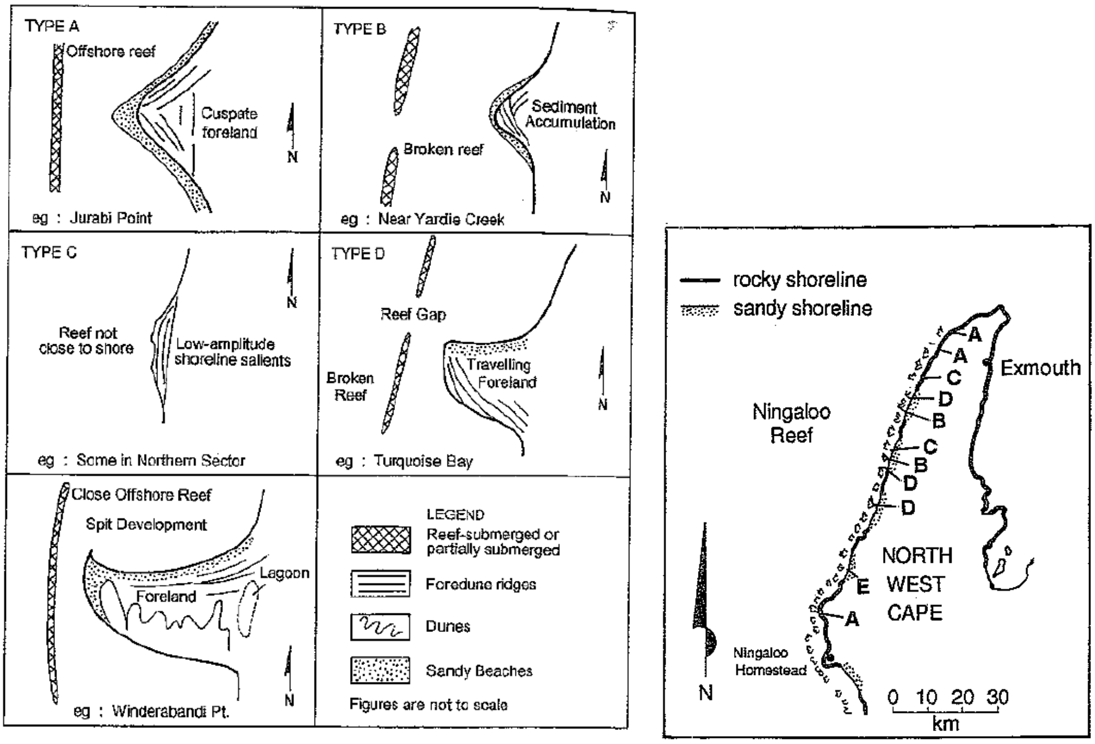


Figure 4-10: Types of Salients, Cuspate Forelands and Tombolos on the Ningaloo Coast Formed in the Lee of Different Reef Structures (Source: Sanderson & Eliot 1996)

4.3.3. Shoreface: Cliffs, Headlands, Bays and Perched Beaches

Rocky headlands, cliffs and perched beaches are highly significant features of the Gascoyne coast. The inherited rocky terrain extensively underlies, and in places outcrops through, unconsolidated sediments some of which are also inherited. The rocky terrain influences coastal vulnerability because it affects responses of accretionary landforms to change in metocean processes. Several forms of rocky headlands, cliffs and perched beaches are recognised in the criteria used to assess vulnerability (Table 2-6; Figure 2-8; Figure 2-11). Broadly following Sunamara (1992), these include plunging cliffs, cliffs and rock platforms, gently sloping rocky coast and beachrock shores. All are found in the Study Area. The high Zuytdorp Cliffs extend over 250km between the mouth of the Murchison River and Cape Inscription on Dirk Hartog Island with breaks in their continuity at False Entrance, Crayfish Bay and South Passage. Low bluffs commonly occur between Learmonth and Giralia. Additionally low bluffs and occasional high cliffs at headlands, such as Goulet Bluff, Eagle Bluff and Cape Peron, form the coast in Shark Bay. The rocky headlands and high cliffs provide vantage points along the coast as well as control points for shoreline configuration in the World Heritage Area. Bluffs with wide platforms and occasional high cliffs also occur along the coast from Point Quobba to Gnaraloo Bay, with high cliffs in the vicinity of Cape Cuvier and Red Bluff; whereas low bluffs, wide platforms and beachrock are common along the Ningaloo coast from near Red Bluff to North West Cape, in the lee of the fringing coral reef.

The diversity of cliff formations in the Study Area is matched by the structural integrity of the materials of which they are comprised. The coastal limestones are recognised as having different degrees of stability depending on the extent to which they have been consolidated since deposition of the sediments comprising them and the degree of degradation the exposed formations have undergone since exposure to metocean processes. Landform Research (2001, 2002) has reportedly conducted risk analyses of coastal limestones in the Shires of Coorow and Carnamah, to the south of the Study Area. Similar studies would be appropriate in the Gascoyne if they have not been undertaken.

Rocky headlands have long been recognised as providing topographic control for the plan shape of the shoreline (Bascom 1980: 14; Silvester & Hsu 1993: 302-312; Masselink & Hughes 2003: 237-241). As part of the rock framework comprising the coast they directly affect the adjacent shore and commonly determine the degree to which the shore is locally exposed. This is particularly significant in Shark Bay where the coast is comprised of long peninsulas separating elongate embayments. Beaches within the embayments are not directly subject to swell and display the characteristics of the very low energy beaches described by Travers *et al.* (2010). More commonly throughout the region, headland promontories are smaller although they may still restrict the extent of sediment movement along the coast. They may also have localised effects on beaches adjoining them. For example, spits and bars are tied to small headlands along the Peron Peninsula in Shark Bay, associated with sediment bypassing. Many headlands in the region have platforms supporting perched beaches, such as those described by Green (2008), da Silva (2010) and Gallop *et al.* (2011). Additionally, the type of barriers developed at bay heads or in the embayments between successive headlands is a function of sediment supply which may be restricted by headlands or redirection of longshore transport.

A perched beach may be defined as an accumulation of unconsolidated sediment atop rocky coastal topography (Larson & Kraus 2000; Doucette 2009; Gallop *et al*. 2011). Semeniuk and Johnson (1985: 233) described such beaches as '*rocky shore with sandy beach*' and noted they permanently have '*a wedge, pockets or continuous ribbon of beach-dune sand overlying inner parts of the platform, notch, high tidal seacliff, supratidal seacliff and bench*'. At the broadest scale they may form the mainland barriers described by Roy *et al*. (1994). Such beaches are geologically controlled, with the interaction between the local metocean processes, available sediment and underlying rock structure governing the beach response. They can undergo rapid changes in width and elevation, partially due to the restricted volume of sediment available for transport. Perched beaches are included in the assessment of vulnerability (Sections 3.2.2 and 3.2.3) but also should be considered n further detail in any local assessment.

An understanding of the perched beach system is required for assessing vulnerability on a local scale. The behaviour of perched beaches is not well described in available literature (Green 2008; Gallop *et al.* 2011); however, some conceptual models describing the behaviour of certain types of perched beaches have been reviewed by Green (2008) and Gallop *et al.* (2011). Many of the models consider cross-shore processes, such as those shown in Figure 4-11. Sediment can be contributed to the beach during low water levels when waves overtop the offshore limit of the rock platform, depositing sediment on the platform. Erosion of the beachface occurs owing to lower wave energy attenuation during high water levels, with sediment deposited seaward of the platform. These beach systems are sensitive to inter-decadal variability in metocean processes, such as periods of higher water levels removing sediment from the beachface.

The elevation of the rock surface underlying unconsolidated coastal sediments in relation to sea level is a critical factor in determining the effects of natural fluctuations in sea level on overlying sand deposits 'perched' above the rock. In some circumstances coincidence of periods of higher than average sea level with storm surge and high waves may erode and trigger instability of frontal dunes. The diversity of possible coastal response warrants consideration of the coastal susceptibility to changing environmental conditions as well as identification of landform elements which are inherently unstable. The two are clearly related. Susceptibility which identifies *potential* landform change is the primary factor, given the form of the rocky topography. The stability of the unconsolidated sandy landforms perched on the rocky topography essentially describes the present condition of the barrier surface and is a secondary consideration. It describes landform change that is *presently* taking place.

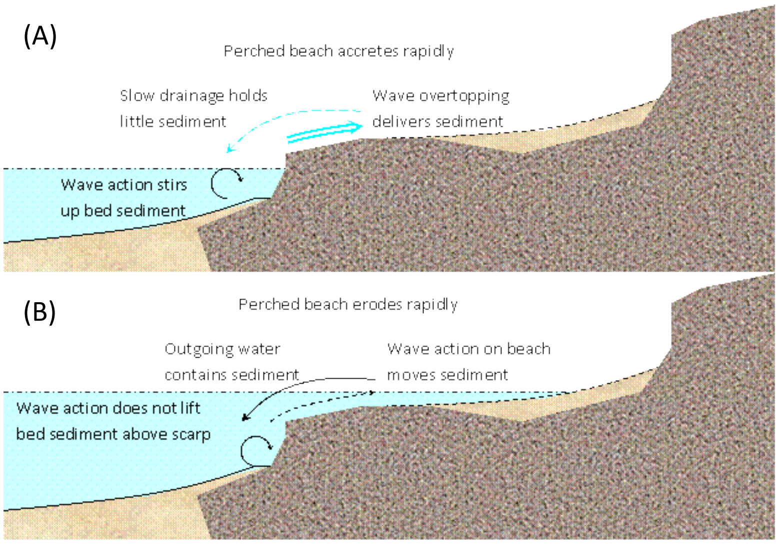


Figure 4-11: Perched Beach (A) Accretion Process and (B) Erosion Process

Further consideration is required into other factors controlling the beach presence and variability, particularly the role of alongshore transport. This includes the planform behaviour of the area, such as any local currents transporting sediment beyond the platform through gaps in reefs or rips and limits to sediment availability by headlands, cliffs and engineered structures. Investigations are required into the sediment transport patterns at the site including: pathways for sediment supply and loss; the episodic erosion patterns (e.g. there may be a storm threshold for erosion); and the disjunction between the erosion and recovery processes (Figure 4-11). On parts of the coast, as near Vlamingh Head, the perched beaches include a line of boulders likely to have been deposited during extreme storm conditions.

A relatively unstable and migratory perched beach could have relatively stable landforms further landward beyond the reach of storm inundation and wave action.

4.3.4. Shoreface: Sub-tidal Terraces and Tidal Flats

Tidal flats are geomorphologic systems that include a variety of coastal landforms (Figure 4-12) ranging from shorelines adjoining broad supratidal salt flats to gently-shelving subtidal terraces extending well offshore (Dyer *et al*. 2000). The full sequence of landforms is apparent across the coast along the Wooramel Bank, between Gladstone and Greenough Point, and the Yannarie coast from Giralia to south of Turbridgi Point , part of which is within the Study Area. In this document the term *mudflat* has been applied to the area of tidal flat above mean sea level; and *terrace* to the mainly subaqueous landform below mean sea level for convenience. *Tidal flat* refers to the whole geomorphic system.

Subtidal and intertidal terraces are common in the sheltered inshore waters of Shark Bay and the western shore of Exmouth Gulf (Brown 1998) as well as in the lee of reefs. In many places terraces are perched on submarine platforms or pavements, as occurs near Eagle Bluff and at Bundegi. Elsewhere a lens of unconsolidated sediment comprises the structure and either merges with barrier terrain to landward or abuts an older land surface, as has been described for the Ningaloo coast by Leeden (2003) and Collins & Twiggs (2011). Sedimentologically, tidal flats in the region tend to be comprised of muddy sand or sandy muds and the terraces of coarser sands and shell, as occurs on several beaches in Shark Bay – particularly L'haridon Bight (Playford 1990).

Tidal flats are areas of marked interaction between rivers and tidal creeks, as well as surface run-off. Flood and ebb flow in tidal channels provides a significant mechanism for cross-shore transport on tidal flats (Rinaldo *et al*. 1999; Pritchard & Hogg 2003). This is a major mechanism of sediment exchange where the channels are connected to estuarine reaches of rivers or tidal creeks draining lagoonal basins and subaerial. The tidal flats are fully active under and immediately following extreme river flooding and surge inundation. During more quiescent conditions rivers and streams may discharge into basins and be indirectly connected to tidal creeks and the ocean. Under these circumstances the mouths of tidal creeks may be closed by littoral drift at times when intermittent streams are not flowing. Commonly, water flow in the creeks and basins, as well as sediment exchange between the tidal flats and inshore marine waters, is determined by tidal condition (Toffolon & Lanzoni 2010). Tidal creek erosion of the subaerial mudflats is apparent through headwater gullying and mangrove intrusion (Woodroffe & Mulrennan 1993; Mulrennan & Woodroffe 1998: Cobb *et al*. 2007). Conversely, deposition by tidal creeks occurs on low-lying fans at the headwaters of the creeks. Switching between erosional and depositional states may occur seasonally or at longer periods in response to variation in mean sea level, which implies the role of mudflats locally fluctuates between a source and a sink depending on metocean conditions and variation in climate (Winn *et al*. 2006).

In addition to their physical significance, tidal flats are important from a biologic perspective (Stal 1995; Sutherland *et al.* 1998; Herman *et al.* 2001; Kuwae *et al*. 2008; Ogburn & Zeng 2010). First, the algal mats formed on mudflats constitute the base of the food chain for many marine species of value for human consumption, particularly crustaceans and juvenile fish. Second, mangrove vegetation along tidal creeks and the coast is biologically highly productive and shelters juvenile species. Third, the tidal flats with their shallow inshore waters are highly productive areas of seagrass and marine algal growth. They are important

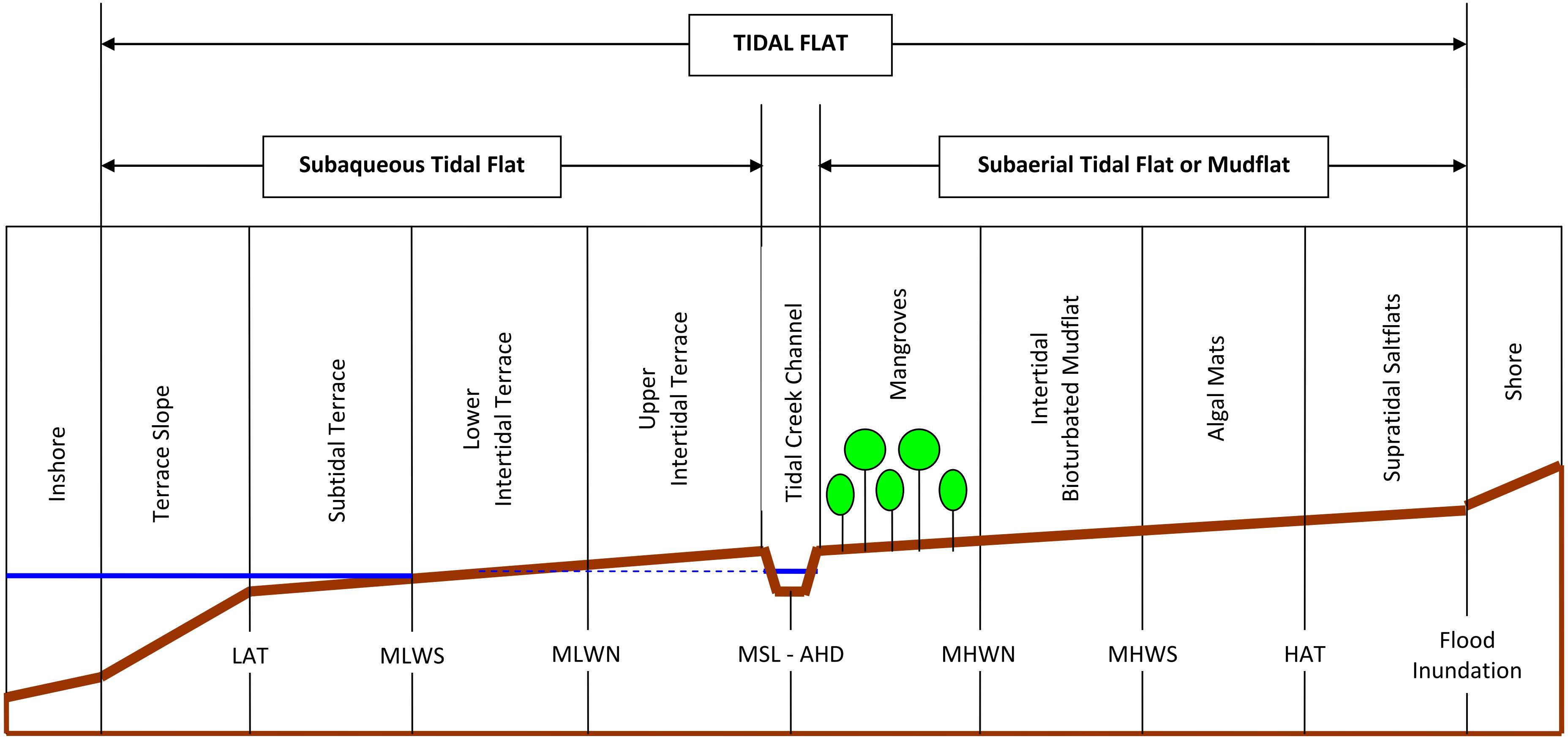


Figure 4-12: Nomenclature Applied to Tidal Flat Environments

Approximate tidal limits are indicated with reference to Australian Height Datum (AHD = 0.0m); Highest Astronomical Tide (HAT); Mean High Water Spring Tide (MHWS); Mean High Water Neap Tide (MHWN); Mean Low Water Neap Tide (MLWN); Mean Low Water Spring Tide (MLWS) and Lowest Astronomical Tide (LAT). Actual tidal heights will vary geographically as well as between environments subject to diurnal and semi-diurnal tides.The full sequence of units is not necessarily present at all mudflat locations. The slope of the surface is commonly less than 2°.

for sediment production as well as for the support of marine biota. A case may be made for management of the tidal flats as essential life habitats.

Subtidal and intertidal terraces switch between sediment sources and sinks, serving similar functions to tidal flats in terms of their biological importance. Sub-tidal terraces are influenced by prevailing wave energy and a general trend for gradual cross-shore sediment transport (Damara WA 2011). Waves breaking along the outer margin of a terrace act to distribute sediment, creating a structure that is relatively smooth in planform. The cross-sectional structure of a terrace is transitory, being a function of the variability in sediment supply and the rate of transfer to adjacent beaches. Supply rates may be increased by higher than normal wave conditions, but under extreme wave events the structure may be destabilised. During periods of low supply, an unconsolidated terrace narrows or may be completely stripped. During extreme events sediment may be transferred from the terrace to the shore or the terrace widened offshore. During periods of high cyclonic activity and higher mean sea levels, sediment may be stripped from the shoreface and brought up onto the terrace from deeper water, raising the elevation and potentially increasing the terrace width.

4.3.5. Groundwater

Groundwater is important for biophysical reasons including water supply, nutrient transport and its affect on coastal stability. Groundwater investigations in the Gascoyne have been completed to determine water supply for townsites, pastoral leases and industrial purposes. For example groundwater conditions have been examined in some detail on the Cape Range (Allen *et al*. 2003; Department of Water 2007; Bennelogia 2008) and in the Carnarvon basin (Department of Water 2007, 2010; Dodson 2009; Magee 2009). More site specific information is required for assessment of groundwater impacts on local coastal processes and coastal stability.

Physical processes in the Gascoyne coastal region vary with the spatial and temporal changes in groundwater levels. There is likely to be high inter-annual variability in groundwater levels related to rainfall activity associated with tropical cyclones, thunderstorms and northwest cloudbands (BoM 1998). Much of the spatial variation is associated with the geologic framework (Department of Water 2007); particularly with inherited basins and palaeochannels such as Gnaraloo Bay and Lake MacLeod. Potentially, coastal areas subject to comparatively high groundwater levels are more susceptible to: flooding of inherited basins and mudflats; reactivation of palaeochannels during extreme events; enhancement of the scour potential of ebb tidal currents on mudflats; and increased rates of beach erosion. The converse applies during phases of drought and low groundwater discharge.

Proposals for development should give due regard to local groundwater conditions and their potential influence on landform stability.

4.3.6. Deltas and Floodplains

Several types of river deltas and floodplains are found in the Gascoyne region. River deltas include the large active delta of the Gascoyne River and two abandoned deltas to the south, the Boodalia and Brown (Johnson 1974). Each of these three systems supports a variety of deltaic landforms including floodplains with overbank basins, palaeochannels, oxbow lakes, gorges and levees. The palaeochannels indicate a geologic and more recent history of channel avulsion, with the main channel of the Gascoyne River switching its location in response to extreme flood events (Johnson 1974). The capacity for avulsion upriver is indicated by the anabranched stream systems and the extensive paleochannel systems over which Boodalia and Brown channels now lie (GEMS 2009).

The many ephemeral streams and creeks of the Trealla and Range Land Systems around Alison Point and Cape Range, sometimes mistakenly referred to as palaeostreams, may have a high discharge during extreme discharge events (Allen *et al.* 1993; Wyrwoll *et al.* 1993; Martens *et al.* 2000). Between the extreme events the river mouths infill and are closed by bar formation, operating as temporary sediment sinks at a local scale.

Inherited deltaic features are associated with the Wooramel River, Gascoyne River (Johnson 1974; Hocking 1990), the river systems draining into Lake MacLeod and the Yannarie River. These features comprise the extensive outwash plains and their adjacent subtidal terraces, such as the Wooramel Bank. Outwash plains are common in the region and are highly susceptible to inundation by terrestrial flooding and storm surge. The sediment supply in these areas is dependent on erosion and reworking of sediments from the inherited features (Wright 1985) together with contemporary sediment sources such as bioproduction on subtidal terraces.

4.3.7. Sediment Availability

Local variability in sediment supply affects short-term stability and long-term susceptibility of coastal landforms through the mutual dependence of coastal processes, sediments and landforms within a fixed geologic framework (Figure 2-6); change one and the other two adjust to the alteration. This connectivity defines coasts comprised of unconsolidated sediment as a morphodynamic system (Wright & Thom 1977) requiring equally detailed consideration is given to the three components in conceptual or numerical modelling of coastal change. Alongshore variability in the supply of sediment from nearshore sources is particularly significant for the landforms of the semi-arid to arid Gascoyne coast because little modern sediment is derived from terrestrial sources, with the exception of a substantial, irregular contribution from the Gascoyne River. Also, the extent of Holocene sediment along the shore is comparatively much less than is apparent in Southwestern Australia. The principal sediment sources within each primary compartment are listed in Table 4-6. General types of sediment sources and sinks are listed in Table 4-7 for applications at different spatial scales.

The intensity and geographic distribution of dominant coastal processes (Section 4.2) varies along the eight primary coastal compartments encompassing the Study Area. An understanding of the processes is important because they:

1. Identify the potential for sediment transport to occur on the coast, without accounting for the availability of sediment and the connectivity of sediment pathways between landforms;

2. Establish time and space scales at which sediment is moved, including, pulsational sediment supply from rivers (Section 4.2.5) and release of sediment from marine sand stores during extreme episodic events; and
3. Explain sediment bypassing of geologically fixed compartment boundaries and the manner in which it occurs.

The concept of sediment supply and availability is included in the assessment of vulnerability through the four categories for Instability (Table 2-6). There is alongshore variability within a sediment cell, with localised sources, transport pathways and sinks (Figure 2-2; Figure 2-3) that fluctuate in capacity and function over time. The volume of available sediment is constrained by the geologic inheritance, for example, there is restriction of the volume of freely available sediment on beaches underlain by rock (perched beaches and dunes– Section 4.3.3) and cliffed coasts.

Unconsolidated, accretionary landforms such as sub-tidal terraces, beaches, cuspate forelands and dunes, are essentially sediment sinks or stores. They are connected to areas of sediment supply by sediment transport pathways along and across their surfaces. Any modification to sediment transport or sediment availability is likely to have a downstream impact on adjacent unconsolidated coast. In this context the future stability of an accretionary landform is commonly dependent on any updrift interference with sediment transport and stabilisation, along with natural variability and changes to metocean processes. Sediment transport interference, such as the installation of a harbour facility, could result in updrift sediment starvation of the beach and inshore, which in turn starves the frontal dune, primary dune and barrier. If an eroding dune is stabilised with revegetation; or as a dune grows or forms a blowout, this can result in sediment loss for the downdrift coast. The instability of the coast is considered with regard to the available sediment, including the vegetation coverage of the dune and barrier, with considerations of landform connectivity required when assessing future instability.

Rocky coast, particularly cliffed coast commonly indicates paucity of sediment availability at the shore. Large cliffs and extensive rock platforms are prevalent along the exposed sections of the Gascoyne coast where the inshore bathymetry is deep, as it is along the Zuytdorp Cliffs and in the vicinity of Cape Cuvier. Elsewhere unconsolidated sediment may be most abundant on the inner continental shelf or shoreface but distributed offshore by the interaction of metocean processes with the rocky topography. In such circumstances terrestrial Holocene landforms are likely to be more limited in their geographic extent. They may be distributed discontinuously along the coast and restricted to the heads of embayments. This is apparent on mixed sandy and rocky coast where the geological inheritance is substantial, such as in Shark Bay where wide, partly-lithified subtidal terraces occur as well as along the shore between Point Quobba and Gnaraloo Bay where low bluffs, beachrock ramps and inshore pavements are prevalent. The susceptibility of mixed sandy and rocky coast to changing metocean conditions is dependent on the geometry of the rocky topography and the location and availability of unconsolidated sediment in relation to it. The variety of mixed sandy and rocky coast landforms present along the Gascoyne coast constitute the perched beaches described in Section 4.3.3 and used as criteria to determine coastal vulnerability.

Table 4-6: Principal Sources of Sediment within each Primary Compartment

Primary Compartment	Secondary Compartment	Principal Sediment Sources
EASTERN GULF Giralia to Locker Point	Giralia to Locker Point	Principal sources include episodic supply from erosion of the mudflats by overland flow across the outwash plain as well as bioproduction in mangrove communities fringing the shore and seagrass meadows on the subtidal terrace.
WESTERN GULF North West Cape to Giralia	Learmonth to Giralia	A major transition in sediment supply occurs between Learmonth and Giralia; with the principal sources including episodic supply from erosion of the mudflats by overland flow across the outwash plain as well as bioproduction in mangrove communities fringing the shore and seagrass meadows on the subtidal terrace. Episodic stream discharge during extreme events may deposit some gravel to the shore between Learmonth and North West Cape. The gravels are mixed with biogenic sediment derived from nearshore platforms and reefs as well as reworked sandy sediment from erosion of frontal dunes.
NINGALOO Alison Point to North West Cape	Winderabandi Point to North West Cape	The fringing coral reef is a major source of biogenic sediment between Red Bluff where it closes with the shore, and Bundegi in Exmouth Gulf. A secondary source is apparent as localised erosion of beaches and dunes, particularly on cuspate forelands where there is differential erosion on the northern and southern flanks of the landforms.
MACLEOD Point Quobba to Alison Point	Gnaraloo Bay to Alison Point	The MacLeod compartment includes an area of low sediment availability, with an exposed rocky shore extending from Point Quobba to Red Bluff; and the start of the Ningaloo Reef complex between Red Bluff and Alison Point where biogenic sediment is derived from the fringing coral reef.
GASCOYNE Grey Point to Point Quobba	South Bejaling Hill to Point Quobba	The Gascoyne compartment includes three major sources of sediment in two sectors. First, sediment is derived from reworking of deltaic sediments and bioproduction in mangrove communities fringing the shore and seagrass meadows on the subtidal terrace flanking the largely inactive Browne and Boodalia deltas; and second, substantial episodic deposition occurs with flooding of the Gascoyne River. Sediments deposited on the active delta of the Gascoyne River are spread northwards from Miaboolya Creek, an overflow distributary of the Gascoyne, to Point Quobba.
L'HARIDON Cape Peron North to Grey Point	Wooramel coast to Grey Point	In the NE part of the compartment, from Gladstone Bay to Grey Point the sediment supply is mainly associated with bioproduction and reworking of sediment on wide subtidal terraces. Bioproduction is expected to increase northwards along the Wooramel Bank with an increase in mangrove cover along the shore. The SE shore is more complex. Between Nilemah coast E and Gladstone Bay the principal sources include episodic supply from mudflat erosion by overland flow across outwash plains as well as bioproduction, and reworking of sediments, on wide subtidal terraces. Sediment supply within the southern part of the L'Haridon Compartment is markedly compartmentalised, particularly within L'Haridon Bight and along the western shore of Hamelin Pool, from Cape Peron to (Kooka Point) Gladstone Bay. It is mainly associated with bioproduction and reworking of sediment on wide subtidal terraces. The compartment is noted for Shell Beach which is comprised of Heart Cockles (*Fragum erugatum)*.

Primary Compartment	Secondary Compartment	Principal Sediment Sources
FREYCINET Cape Inscription to Cape Peron North	Goulet Bluff to Cape Peron North	Sediment supply within the Freycinet Compartment is markedly compartmentalised within Denham Sound, Freycinet Reach and Henri Freycinet Harbour and is mainly associated with bioproduction and reworking of sediment on wide subtidal terraces as well as reworking of sediment associated localised dune erosion.
ZUYTDORP Murchison River to Cape Inscription	Steep Point to Cape Inscription	Sediment deposited by the Murchison River and reworked from the inner continental shelf form beaches and dunes in shallow embayments between the river mouth and Nunginjay Springs. There is a low supply from cliff erosion and reworking of Tamala Limestone along the Zuytdorp Cliffs between Nunginjay Springs and Zuytdorp Point (False Entrance).

Table 4-7: Sediment Sources and Sinks
(After: Bowen & Inman 1966; van Rijn 1998)

Source	Sink
Biogenic deposition (e.g. from seagrass banks)	River mouth bars, deltas and alluvial landforms
Reworking of cliffs, beach rock, ridges and reefs	Dunes and sand sheets via eolian transport
Longshore transport into the area from beaches and inshore areas	Offshore transport into inshore areas
Wind transport onto the beach offshore from the foredunes and transport along the beach	Offshore transport into lagoons and gaps within the reef structure; and submarine canyons.
River floods (including mobilisation of bar, alluvial and inshore sediments)	Longshore transport out of the area
Onshore transport	Solution and abrasion
Beach nourishment	All the above categories

4.4. LOCAL MEASUREMENTS

Site specific information derived from local measurements of winds, water levels, waves, currents and hydrology may be used for local coastal process investigations. Variability between sites suggests this information is largely not transferrable between locations. However, it is useful for verification of numerical models.

4.4.1. Winds

Four long-term wind observation stations near to the Gascoyne coast are at Kalbarri, Denham, Carnarvon and Learmonth (Figure 4-1; Table 4-8). The longest set of observations is at Carnarvon Airport, since 1945.

Wind datasets in the Gascoyne focus on population centres, originally installed for airfields and farming, with improved coverage through automatic weather stations in the 1970s and 1980s. There are limited stations near the coast. Further wind datasets for coastal stations, not included in this investigation, are recorded at:

- Milyering, 20km north of Sandy Bay, by the Australian Institute of Marine Sciences (AIMS) from 12 February 1997 to present (AIMS 2010; Taebi *et al.* 2011);
- Offshore locations on the Exmouth Plateau and North West Shelf (Heyward *et al.* 2006);

- Historic wind datasets held by Bureau of Meteorology (Bureau of Meteorology Station List online):
    - Exmouth Town Station 5051 from June 1967 to February 1975;
    - Associated with Navy operations at Point Murat at Navy Alpha Station 5075 from December 1971 to June 1976 and Navy Charlie Station 5060 March 1968 to November 1971;
    - Vlamingh Head Station 5024 from January 1965 to March 1967;
    - Cape Cuvier Station 6094 from June 1972 to July 1975; and
    - Hamelin Pool Station 6025 from January 1957 to April 1980.

Regional wind information can be obtained from numerical models such as NCEP Model Reanalysis Program and ACCESS. The NCEP Reanalysis Program is the National Centers for Environmental Protection produced by the National Oceanica and Atmospheric Administration (NOAA). The Australian Community Climate and Earth-System Simulator (ACCESS) suite of models is produced by the Australian Bureau of Meteorology (BoM). The ACCESS models replace the prior Global Assimilation and Predication (GASP), Limited Area Prediction System (LAPS), Tropical Limited Area Prediction System (TLAPS), Mesoscale Limited Area Prediction System (Meso-LAPS) models as of 30 July 2010. These models have limited capacity to represent seabreezes and tropical cyclones due to the spatial resolution of the models (Hsu 1988).

Recorded winds are affected by geography, topography and instrument height and are often representative on winds on a local scale. Of the stations considered here, Kalbarri is 1km inland on a northwest facing coast (6m), Carnarvon is 1.5km inland on a southwest facing coast (4m), while Denham (9m) and Learmonth (5m) are located on the eastern and western side of Peninsulas respectively. Denham is located within Shark Bay with westerly sheltering by the Caparang Peninsular and Dirk Hartog Island. Learmonth is partially sheltered from westerly winds by the elevated Cape Range and experiences the north to northeasterly seabreeze of Exmouth Gulf.

Table 4-8: Wind Observations for the Gascoyne Coast (Source: Bureau of Meteorology)

Station	Location	Lat. (S)	Long. (E)	Height (m)	Dates	50% Wind (km/hr)	90% Wind (km/hr)	Max Obs. (km/hr)
5007	Learmonth Airport	22.241°	114.097°	5.0	1975-2010	16.6	29.5	166.7
6011	Carnarvon Airport	24.888°	113.670°	4.0	1945-2010	20.5	33.5	96.5
6044	Denham	25.926°	113.532°	9.0	1988-2010	20.5	37.1	72.4
8251	Kalbarri	27.712°	114.165°	6.0	1970-2010	13.0	27.7	126.0

The seabreeze and sustained geostrophic winds result in prevailing southerly winds along most of the Gascoyne coast, switching from approximately southeasterly in the morning to southwesterly in the afternoons. This is demonstrated at the Kalbarri, Denham and Carnarvon stations. Exceptions to this sea breeze trend are caused by differences in the coastline orientation, particularly complex coastline shapes around Shark Bay and Exmouth Gulf (BoM 1998). For example, within Shark Bay winds at 4pm at Hamelin Pool have a westerly bias and at Denham they are predominantly southerly. Areas on the north and east of the Cape Range Peninsula, such as Learmonth, may experience both the southwesterly and north to northeasterly seabreeze of Exmouth Gulf, with either effect dominant with potential transitioning between the two seabreezes within one day (Hearn *et al.* 1986; BoM 1998). The northeasterly seabreeze may be overwhelmed by the southwesterly seabreeze in late afternoons, particularly in summer. The northeast seabreeze occurrence decreases to the north towards North West Cape.

The dominant wind directions display a diurnal pattern (Figure 4-13) indicating the significance of seabreezes in the region, overlying sustained geostrophic winds.

- At Kalbarri and Carnarvon, the dominant wind directions are within the SE quadrant in the morning and from S to SW in the afternoon.
- At Denham, the dominant wind directions are from the SE to SW in the morning and from the S to SW in the afternoon.
- At Learmonth, the dominant wind directions are from the SE to SW in the morning and bimodal within the SW quadrant and from the NE quadrant in the afternoon.

Any localised changes in direction and intensity of the prevailing winds, including the sea breeze, modifies the: local wind-wave climate (sea); longshore rates of sediment transport; eolian (wind-driven) transport of sediment from beaches to the dunes; orientation and likelihood of dune blowouts; and landform alignment. The prevailing wind direction should be considered in conjunction with the coastal aspect for determining coastal access and the proximity of development to dune blowouts and migrating sandsheets.

There is a seasonal difference in the strongest winds in the Ningaloo area (Damara WA 2006c). Intense synoptic features, interaction between pressure systems or the coalignment of thermal and geostrophic winds may produce strong winds. Winter strong winds may be produced from any direction. The coalignment of thermal and geostrophic winds may occur in summer, with strong southerlies. The most extreme sustained winds are produced by tropical cyclones, with wind direction dependent on the system path.

Wind observations at Kalbarri, Denham, Carnarvon and Learmonth over the period of record have shown considerable interannual variability. Annual summations of the 9am wind speed cardinal components (E-W and N-S) have been used to examine whether there are any apparent patterns of change or standout years (Figure 4-14). The 9am wind indicates the prevailing winds with limited influence of the seabreeze. These records are influenced by the passage of tropical cyclones.

Figure 4-14 shows the net annual easterly and northerly drifts at Kalbarri, Denham, Carnarvon and Learmonth stations.

- Kalbarri had periods of stronger easterlies in the mid 1970’s and mid 1990’s and weaker easterlies in the 1980's to early 1990's and in the 2000's, potentially attributed to a north-south shift in the sub-tropical ridge (BoM 1998). Short periods of strong southerlies are evident around the years 1980 and 1990, while a sustained period of weak southerlies has occurred from the mid 1990's onwards.
- The short nature of recordings at Denham limits the assessment of interannual variability; however a period of stronger southerlies occurred around the year 2000.

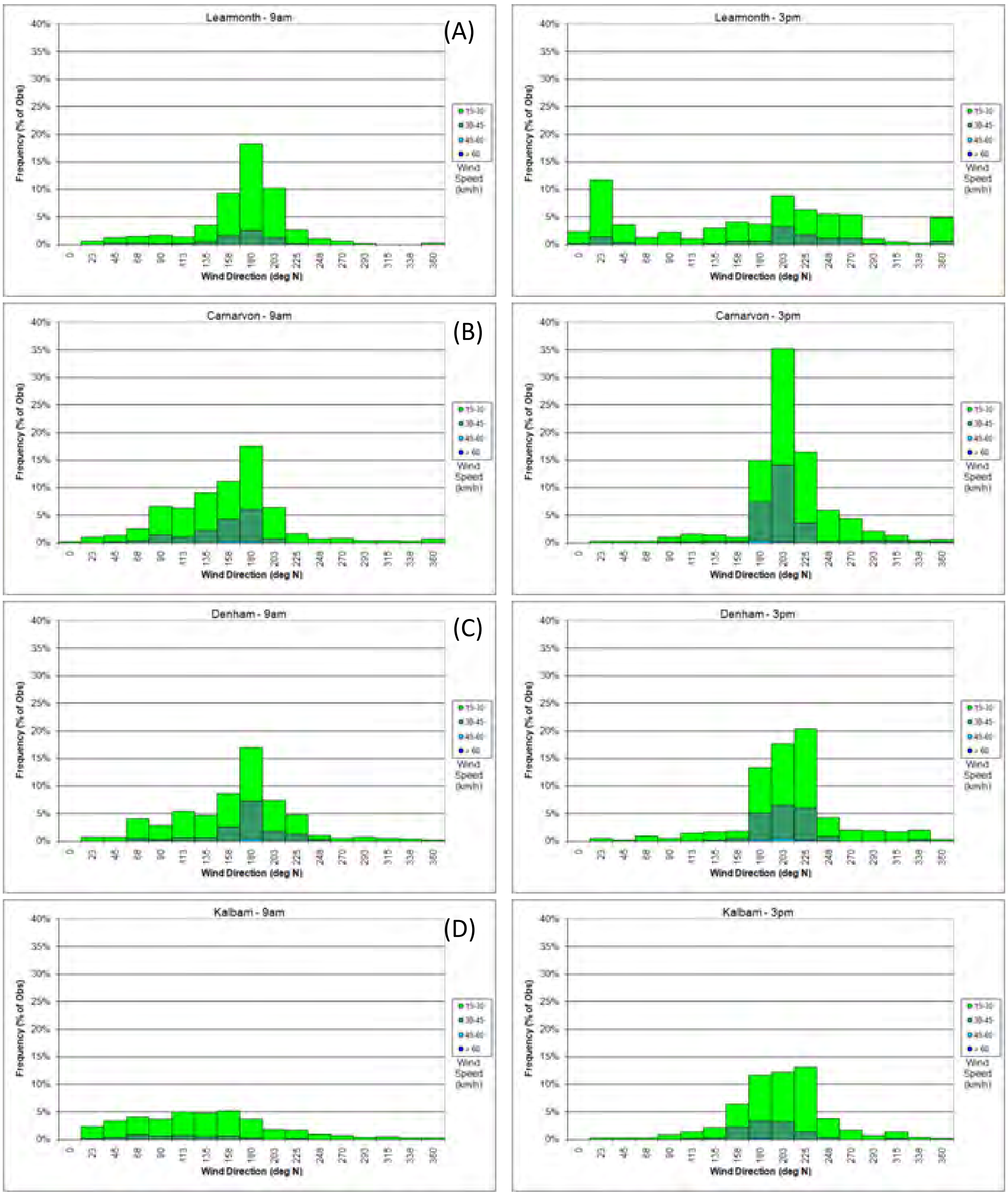


Figure 4-13: Wind Speed and Direction Frequencies for 9am and 3pm (A) Learmonth, (B) Carnarvon, (C) Denham and (D) Kalbarri (Source: Bureau of Meteorology)

- Carnarvon displays three distinct periods of strong easterlies around the year 1950, in the mid 1960's and around the year 2000 and three periods of weak westerlies around the year 1960 and in the 1980's to early 1990's and mid 2000's. Sustained patterns in the northerly wind drift are less apparent, although a period of strong southerlies occurred in the mid 1950's and mid 2000's.
- Learmonth had periods of strong easterlies around the year 2000 and late 1980's and periods of weak easterlies in the early 1980's and 1990's. Variability in the northerly wind drift is relatively minimal.

The directional data at each of the four locations changed from 22.5° bands to 10° bands in 1994, increasing the directional resolution. Carnarvon and Learmonth upgraded to 1° band recordings in 2001. Instrumentation changes at Carnarvon may also have contributed to a shift in the velocity scale, with recent recordings having reduced frequency of strong winds.

4.4.2. Water Levels

Carnarvon has the most sustained water level measuring station for the Gascoyne coast, with the second longest record at Exmouth (Figure 4-1; Table 4-9). Other shorter term water level measurements at Areas of Planning Interest have been recorded at Denham, Monkey Mia and Coral Bay. Further datasets have been collected within Shark Bay (Useless Loop and Hamelin Pool), at Ningaloo Reef (Cape Cuvier, Sandy Bay and Tantabiddi) and within Exmouth Gulf (Point Murat, Point Lefroy, Giralia Point and Fly Island).

Most of the short-term datasets were collected to derive tidal constituents and facilitate tidal predictions (Department of Defense 2010). The capacity to resolve tidal and non-tidal phenomena is determined by the observation length, with deployments less than 12 months unable to distinguish tidal constituents of similar period (Pugh 1987). Datasets of 19 years demonstrate a complete nodal cycle and over 30 years of data are appropriate to analyse for mean sea level trends (Douglas *et al*. 2001; Haigh *et al*. 2011). There is no data length appropriate for the description of tropical cyclone storm surges due to their singular nature and range of contributing processes, although a commonly applied rule of thumb requires at least 33 years data to provide an estimate of the '100 year storm'.

The Carnarvon dataset has reliable recordings since 1966, after the Australia Height Datum was established from 1965 (Easton 1970; Wallace 1988). The Carnarvon tide gauge was originally located on the Carnarvon Jetty, located on the west side of Babbage Island (Damara WA 2008) which was fully exposed to oceanic influences. In 1973, the gauge was relocated to Carnarvon Boat Harbour, which is constructed inside a small basin, connected to Teggs Channel via a dredged channel. The change of location is likely to have affected the relative proportions of surges and seiches experienced. The water level record is shown in Figure 4-16. It is noted that the two of the highest water levels since 1966 recorded during TC Herbie (+2.30m CD) in May 1988 and TC Vance (+2.41m CD) in March 1999 at Carnarvon are not shown due to a data gap in 1988 and instrument failure during Vance (DPI 2003). Numerous reports have been completed on the water levels and storm surge in the region (Hopley & Harvey 1978; Sinclair Knight & Partners 1981; Fandry *et al.* 1983; Wallace & Boreham 1990; DPI 2003). A detailed storm surge study for Carnarvon, including cyclonic storm surge modelling, was recently completed (GEMS 2009).

At Exmouth, water levels have been measured at Exmouth Jetty from 1989-1993 and then in the Exmouth Boat Harbour from 1997 onwards (Figure 4-15; Table 4-9). The Exmouth water levels are recorded from the western side of Exmouth Gulf, with potential for locally generated surge and seiches to be modulated by the bathymetric structure of the gulf (Steedman & Russell 1986; Nott & Hubbert 2005; Damara WA 2006c). The surge recorded during TC Vance (4.89m CD) in March 1999 is significantly larger than any other surge recorded by the tide gauge (Damara WA 2008). A number of analyses of water levels and surge have previously been conducted for the purpose of small craft facilities at Exmouth

(Maunsell & Partners 1981; Riedel & Byrne 1986; Steedman & Russell 1986; Steedman 1987; Coastal Information & Engineering Services 1996; and Egis Consulting 1999a). The findings of these studies are summarised and reviewed in Damara WA (2006c), incorporating the longer-term water level record and the influence of TC Vance (Egis Consulting 1999b). Significantly, the analysis of measured water levels suggests larger non-tidal (surge) variability at Exmouth than had previously been modeled.

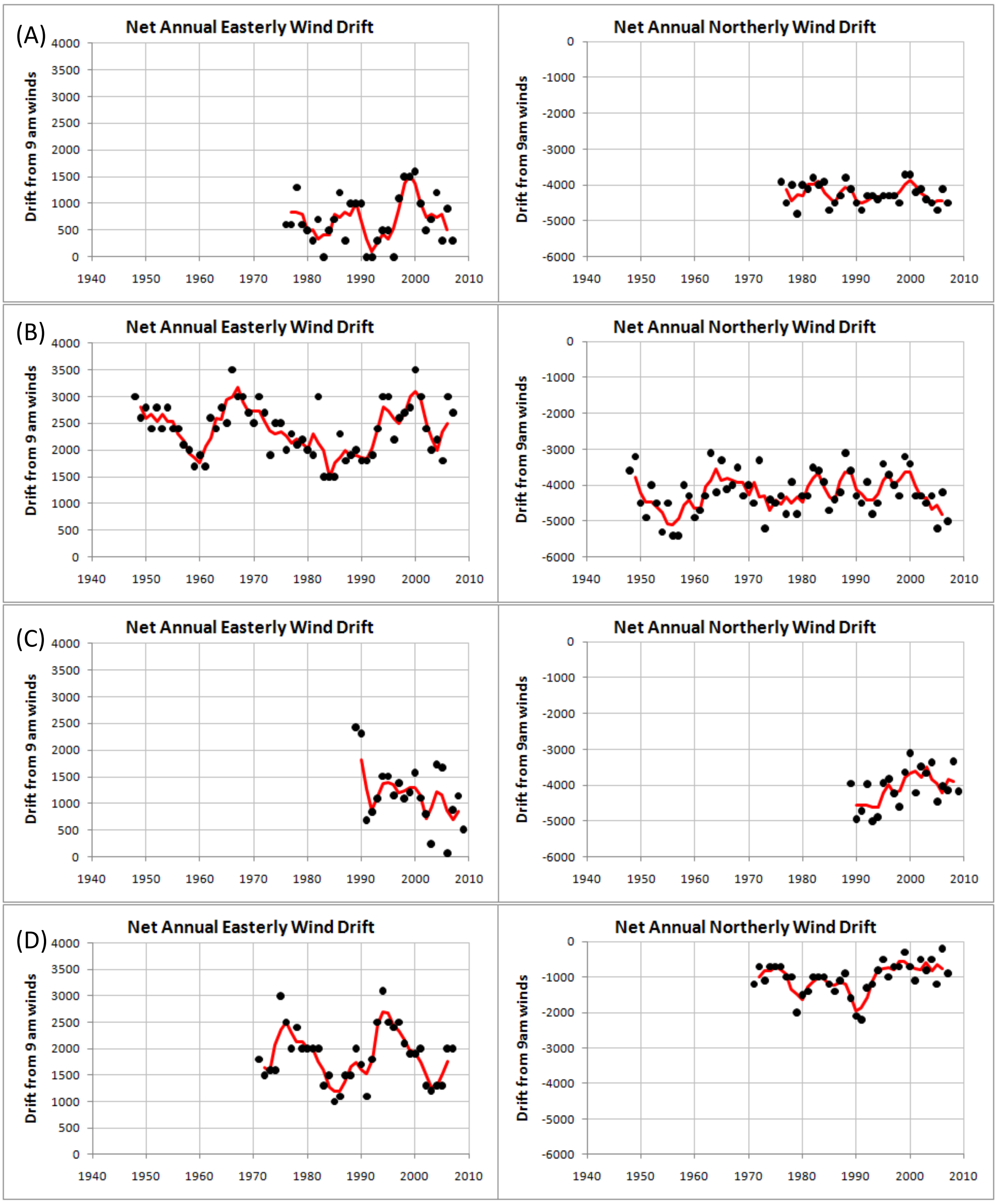


Figure 4-14: Annual Easterly and Northerly Wind Drift
(A) Learmonth, (B) Carnarvon, (C) Denham and (D) Kalbarri

Table 4-9: Water Level Observations Presented for the Gascoyne Coast (Source: Royal Australian Navy Hydrographic Office; DoT; Department of Defence 2010)

Station	Location	Lat. (S)	Long. (E)	Dates
62435	Exmouth	21.955°	114.141°	(1) Nov-1989 to Jun-1993; (2) Feb-1997 to Dec-2008
62370	Carnarvon	24.899°	113.651°	(1) Jan-1966 to Jul-1976; (2) Sep-1977 to Oct-1982; (3) Apr-1984 to Aug-1986; (4) May-1989 to Nov-2008
62341	Denham	26.089°	113.418°	(1) Jun-1979 to Jul-1980

Short periods of water level measurements have been recorded within Shark Bay at the Areas of Planning Interest of Denham and Monkey Mia (Burling *et al.* 2003; MP Rogers & Associates 2004a). At Denham, approximately one year of water levels measurements were recorded from June 1979 to July 1980 (Table 4-9). A time series comparison of the water levels recorded over the same period at Carnarvon is shown in Figure 4-17. Water levels were also recorded at Denham from July 1986 to December 1989, coincident with a tide gauge at Monkey Mia from July to November 1988 (MP Rogers & Associates 2004a).

Wallace & Boreham (1990) considered storm surge at Denham using the short datasets available; however, it did not contain any cyclonic events and is hence unsuited for extrapolation to represent extreme cyclonic surges (DPI 2005a).

Datasets from around Shark Bay have been used to derive tidal constituents (Department of Defence 2010) which were then used to validate numerical models of the tidal behavior of Shark Bay and surrounds (Burling 1998; Burling *et al.* 2003; Nahas *et al.* 2005). This follows from a prior assessment in the 1960s of tidal behaviour and currents of Shark Bay and their effect on sedimentary environments by Logan & Cebulski (1970).

Water levels were recorded from 21 December 2004 to 30 March 2005 at Coral Bay, with wave and current measurements (AWAC meter), to facilitate the design of a boat launching facility by the Department for Planning and Infrastructure (Damara WA 2006a); and from 1991 to 1993 at Monck Head by the Department of Transport (CMPS&F 1997). The water levels are not included in this report as they were not presented against longer-term datasets at Carnarvon or Exmouth. Information on water levels for Coral Bay, including tropical cyclonic extremes, is discussed within Hearn *et al.* (1986), for the design of the proposed Coral Coast Resort (Port & Harbour Consultants 1989; Steedman Science & Engineering 1989; MP Rogers & Associates 1994), for the design of the Coral Bay boating facility (CMPS&F 1997; Egis Consulting 1999c; DAL Science & Engineering 2002; Damara WA 2003; DPI 2005b) and in consideration of storm surge levels at Coral Bay (GEMS 2005b).

Further water level measurements have been recorded at locations within Shark Bay, Ningaloo Reef and Exmouth Gulf. These datasets are not considered within this report as they are not located within an Area of Planning Interest. These include:

- *Shark Bay*
    - Continuous water level measurements at Useloop Loop Jetty by Shark Bay Salt and Department of Transport (Permanent Committee on Tides and MSL 2011);

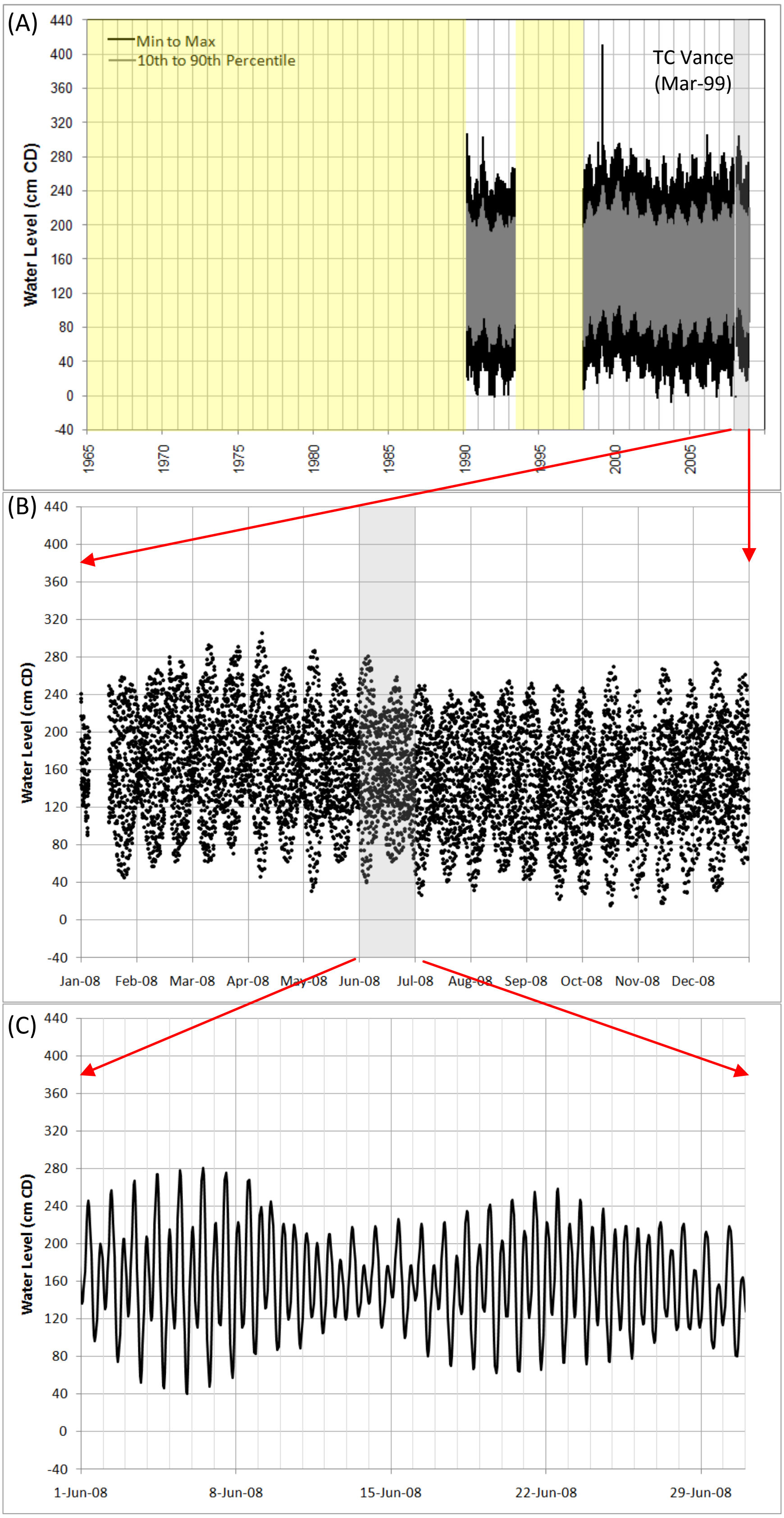


Figure 4-15: Water Levels for Exmouth (1990-1993 & 1997-2008)
(A) Total Record, (B) 2008 and (C) June 2008
(Source: Royal Australian Navy Hydrographic Office and Department of Transport)

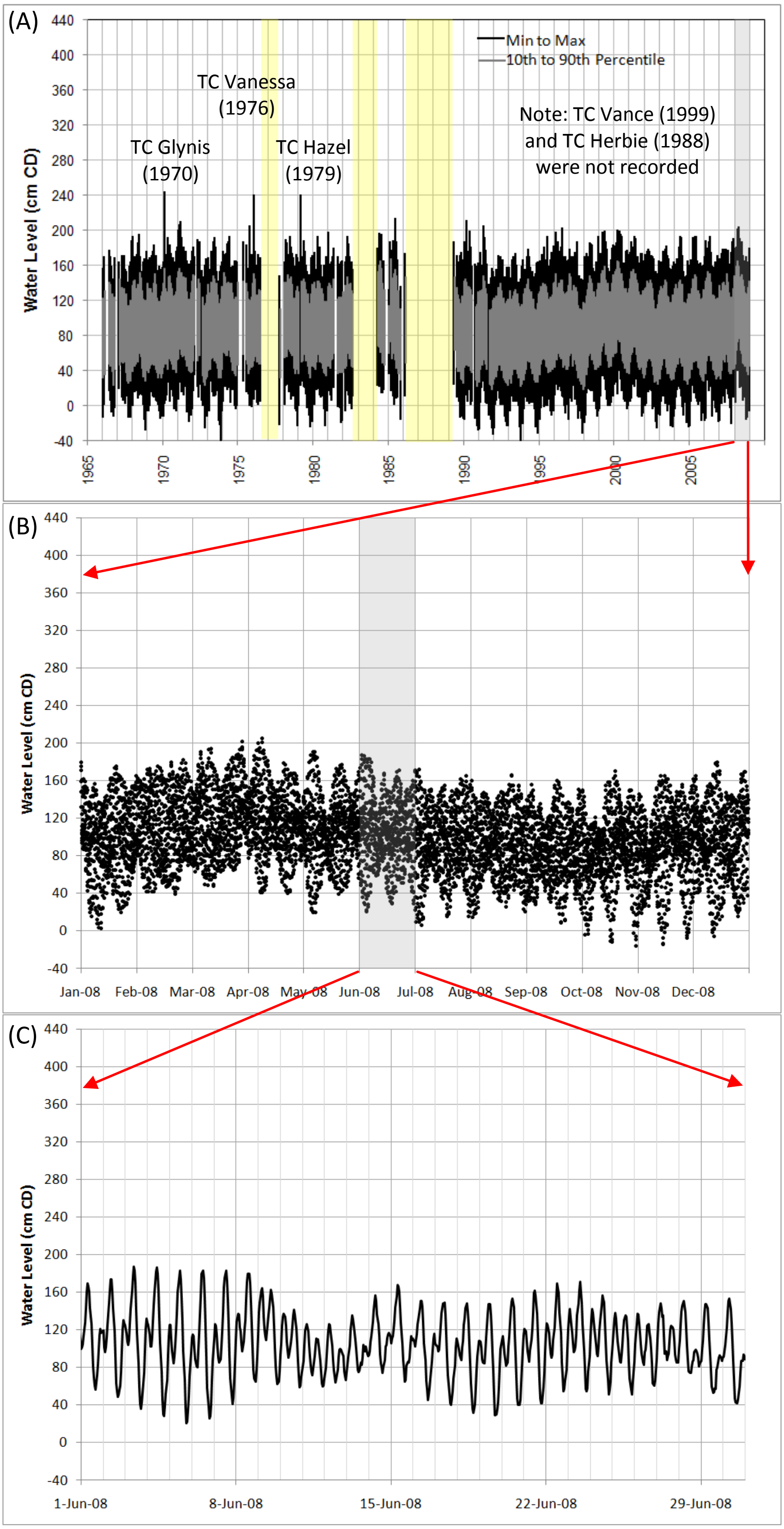


Figure 4-16: Water Levels for Carnarvon (1966-1976, 1978-1982, 1984-1986 & 1989-2008)
(A) Total Record, (B) 2008 and (C) June 2008
(Source: Royal Australian Navy Hydrographic Office and Department of Transport)

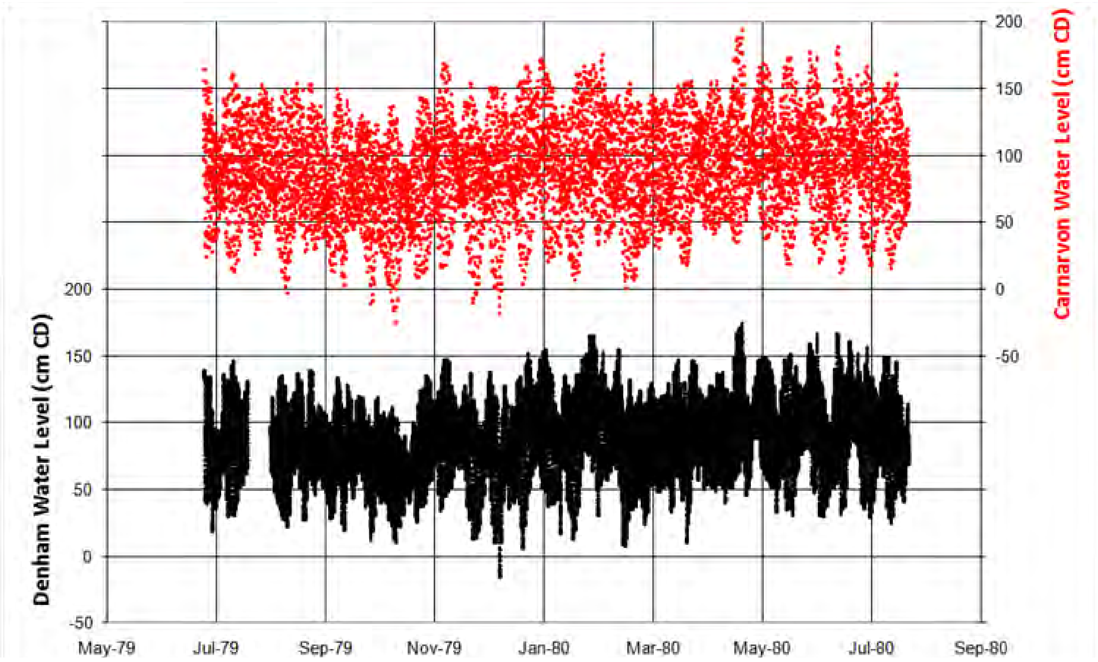


Figure 4-17: Water Levels for 1979-1980 for Carnarvon and Denham (Source: Royal Australian Navy Hydrographic Office)

- A tide gauge installation at Flint Cliff, Hamelin Pool, between October 1983 and April 1985 (Burne & Johnson 2011).
- A tide gauge at Flagpole Landing, Hamelin Pool, between June 1979 and August 1980 by the Department of Marine and Harbours (Playford 1990).

- *Ningaloo Reef*
  - A continuously logging tide gauge at Cape Cuvier has been in operation for the jetty by Rio Tinto Salt, with joint management with the National Tidal Centre (Intergovernmental Oceanographic Commission 2011).
  - Water levels recorded for six weeks (April-May 2006) at three locations along a 4 km stretch of coast within Sandy Bay in conjunction with a suite of other measurements (Brinkman *et al.* 2007; Taebi *et al.* 2011).
  - Short -term water level measurements on the Tantabiddi moorings at 50 and 100m depths in March to May 1999 (including TC Vance), 2002-2003, 2007 and 2009 (Brinkman *et al.* 2007; AIMS 2008).
  - Water levels at Tantabiddi and Exmouth in 1989-1993 (Damara WA 2006d).
  - Water levels recorded for one month in August to September 2008 at 32 and 54m depths offshore of Point Cloates (Brooke *et al.* 2009).
  - Two weeks of water levels recorded by the Australian Institute of Marine Sciences from November to December 1997 approximately 3 km southwest of Vlamingh Head, in conjunction with wave and current measurements. Water level measurements were conducted at four locations, two inshore and two offshore of the reef (AIMS 1997a; Brinkman 1998; Massel & Brinkman 1999).
- *Exmouth Gulf*
  - Water levels collected by the Australian Institute of Marine Sciences within Exmouth Gulf largely from 1994 to 1996, included Point Murat, Point Lefroy, Giralia Bay, Fly Island (AIMS 1997b; Massel & Brinkman 1997; Scott 1998; Verspecht 2002; Heyward *et al.* 2006).

- Water level measurements may be conducted in future at Hope Point (EPA 2008), with numerical modelling of the area conducted by WorleyParsons (2005).

4.4.2.1. Water Level Processes

Key water level processes affecting the Gascoyne coast include tides, atmospheric surges, resonant phenomena, seasonal and inter-annual mean sea level variations (Section 4.2.3). An analysis of the range and standard deviations of hourly water levels at Carnarvon and Exmouth have been included to describe the relative influence of tidal and non-tidal water level signals at these two locations (National Tidal Facility 2000; Eliot 2010). The water level time series was decomposed into approximations for mean sea level (30 day running mean), tide (Doodson-x_o filter) and surge (residual), with some overlap between the approximations (Table 4-10). Here the surge signal is likely to include resonant phenomena. The relative standard deviations indicate that tides provide the most consistent contribution to water level processes at both Carnarvon and Exmouth, with mean sea level and surge providing a much smaller contribution. The relative ranges at Exmouth also support the importance of tide, however at Carnarvon the relative range of tide and the non-tidal component are of similar ratio suggesting that non-tidal water level fluctuations can occasionally be as significant as tidal fluctuations. The datasets are affected by the passage of tropical cyclones.

Table 4-10: Mean Sea Level, Surge and Tide Approximations

	Exmouth (1997-2008)		Carnarvon (1989-2008)	
	Range	Std. deviation	Range	Std. deviation
Water Level (cm CD)	-9 to 411 (420)	53	-40 to 212 (252)	35
Mean Sea Level (cm)	126 to 180 (54)	12	63 to 124 (61)	12
Surge (cm)	-21 to 60 (81)	6	-30 to 49 (79)	8
Tide (cm)	-107 to 103 (210)	51	-73 to 67 (140)	32

Water levels can modify the attenuation of wave energy across the reefs of the Gascoyne coast, the breaking wave angle and the area of breaking wave zone on the shoreface.

4.4.2.2. Tides

The Gascoyne is a transitional region, with variation in the dominance of diurnal and semi-diurnal tidal consistuents across the region. In general, tides to the north of the Carnarvon are mixed mainly semi-diurnal and to the south of Shark Bay are mixed mainly duirnal, while the Shark Bay region represents a transition between dominant diurnal and semi-diurnal tide regimes (Damara WA 2006b). However, this variation is inconsistent with local bathymetry enhancement of tidal constituents providing geographical variation in tidal character (Burling *et al*. 2003). The sea level response to tidal potential is enhanced where the water body is resonant with a particular cycle, or where frictional effects cause tidal currents to slow (Damara WA 2008).

Denham, Carnarvon and Exmouth are three of the Standard Ports defined by the Royal Australian Navy Hydrographic Office, with annual tidal predictions published in the Australian National Tide Tables (Department of Defence 2010). Kalbarri and Monkey Mia are secondary ports within the Study Area, with tidal levels derived from harmonic constituents. In general, the tidal range increases to the north from 1.1m (micro-tidal) at Kalbarri to 2.8m (meso-tidal) at Exmouth (Table 4-11).

The structure of Freycinet and Hopeless Reaches determines significant differences in tidal character across Shark Bay (Burling *et al.* 2003; Figure 4-18). The western reach, Freycinet, is principally diurnal as measured at Denham and Useless Loop; and the eastern reach, is principally semi-diurnal as measured at Monkey Mia and Hamelin Pool (Burling 1998; Burling *et al.* 2003). Additionally, a greater tidal range is evident at Monkey Mia compared with Denham and Carnarvon (Table 4-11; Figure 4-17).

Table 4-11: Tidal Planes for Exmouth, Carnarvon, Denham and Kalbarri (Source: Department of Defence 2010)

Tidal Level		Water Level (mCD)				
		Exmouth	Carnarvon	Monkey Mia	Denham	Kalbarri
Highest Astronomical Tide	HAT	2.8	2.0	2.3	1.5	1.1
Mean Higher High Water	MHHW	2.3	1.5	1.8	1.2	0.7
Mean Lower High Water	MLHW	1.7	1.3	1.5	0.9	0.5
Mean Sea Level	MSL	1.5	1.0	1.2	0.8	0.5
Mean Higher Low Water	MHLW	1.1	0.8	1.0	0.7	0.4
Mean Lower Low Water	MLLW	0.5	0.6	0.6	0.4	0.3
Lowest Astronomical Tide	LAT	0.0	0.0	0.0	0.0	0.0

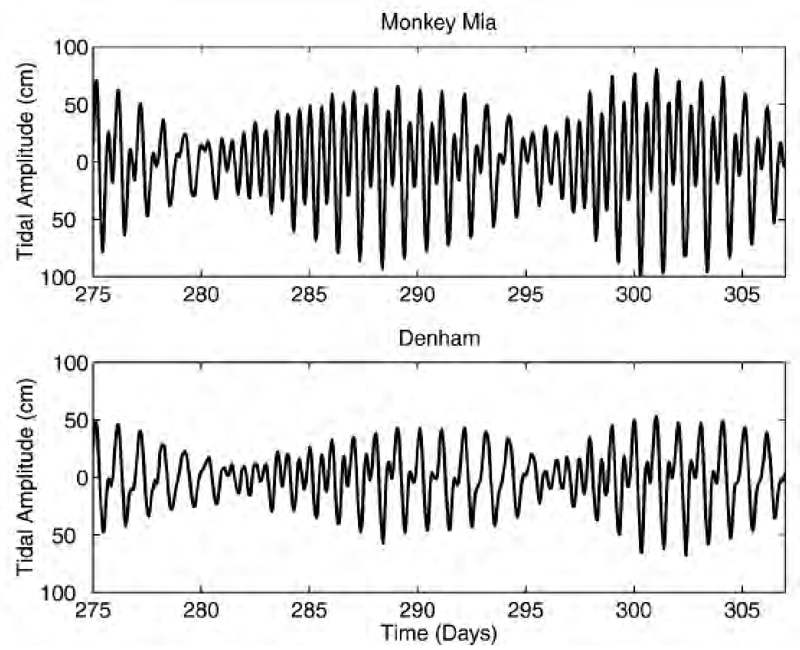


Figure 4-18: Time Series of Observed Tides for October 1988 at Monkey Mia and Denham (Source: Burling *et al.* 2003)
Note: Data smoothing has been conducted to extract the tidal signal

The tidal sequence is affected by monthly spring-neap cycles, bi-annual and inter-annual signals (Figure 4-15; Figure 4-16). The tidal range varies on a bi-annual cycle, with solstitial peaks in June and December for the mainly diurnal tides with transition to equinotical peaks in March and September for the mainly semi-diurnal tides. The tidal sequence is further modulated by the 4.4-year lunar perigee and 18.6-year lunar nodal cycles (Damara WA 2008; Eliot 2010). For diurnal tides, the lunar nodal cycle is dominant, resulting in a 20% variation in maximum daily tide range between low and high years (Damara WA 2008), with apparent peaks in 1987 and 2006. For semi-diurnal tides, the lunar perigean cyle is dominant, with the last peak in 2006 and the next peak due in 2011 (Eliot 2010).

4.4.2.3. Surges

Surge from mid-latitude depressions and tropical storms contribute to the water level signal, although the tides are the dominant water level process at both Carnarvon and Exmouth (Table 4-10). The majority of surge may be atmospheric in origin, a combination of barometric effect, wind and wave setup, related to mid-latitude storms (Provis & Radok 1979). These storms result in peaks in surges occuring at Carnarvon between June and August (Damara WA 2008). In general, the frequency and magnitude of surges resulting from mid-latitude depression decrease to the north of the study area and their contibution to the water level record is reduced at Exmouth in comparison to Carnarvon. It is noted that the typically smaller tidal range and the increased mid-latitudes storms in the southern region of the study area (i.e Kalbarri), the surge contribution is greater.

Surges may also occur due to more unusual meteorological events, such as TC Glynis in 1970 and TC Vance in 1999 which produced the highest water levels on record at Carnarvon and Exmouth respectively. Although cyclonic surges may be large in amplitude and may induce substantial beach responses, they are generally low in frequency and their significance for extreme water levels is determined by their timing relative to high tides. Due to the similarity in scale of tide range and cyclonic surges in the region, analysis of extreme water levels requires a careful understanding of both tidal phenomena and cyclonic surges.

Surges may be locally enhanced due to the orientation and embayed nature of the shore, shelf and nearshore bathymetric structure (Jelesnianski 1978; Damara WA 2009; Section 4.3.1).

4.4.2.4. Resonant Phenomena

The water level record includes a number of resonant phenomena which are developed through the interaction of atmospheric-induced water level movements with coastal configuration (bathymetry and plan form). These phenomena include harbour and bay seiches, continental shelf waves, edge waves and tsunami (Allison & Grassia 1979; Pattiaratchi & Eliot 2008; Eliot & Pattiaratchi 2010; Wijeratne *et al.* 2011).

Resonant phenomena play a significant role in the persistence of water level variations after an environmental perturbation (Rabinovich 2008). Resonance within the Gascoyne region, including seiching, has been specifically identified as a result of coastal lagoon structure (Allison & Grassia 1979; Petrusevics *et al.* 1979). Forcing mechanisms may include storm systems, pressure jumps or thunderstorms, the latter of which are more common in summer than winter (Wijeratne *et al*. 2011). The potential for bathymetric enhancement of locally generated surge and seiches increases within the shallow Exmouth Gulf, particularly towards the southern areas (Steedman & Russell 1986; Nott & Hubert 2005; Damara WA 2006a).

Continental shelf waves, often remotely generated by tropical cyclones, can positively interact with atmospheric surge (Figure 4-19; Eliot & Pattiaratchi 2010; Section 4.2.1). A shelf wave of 0.75m, generated by TC Bianca, was recorded at Carnarvon in March 2011.

Tsunami generated in the Indian Ocean can result in high water levels associated with the leading waves as well as local seiches on the shelf, with a high water level residual of 1.14m recorded at Carnarvon during the 2004 Tsunami (Pattiaratchi & Eliot 2008; Section 4.2.2.1).

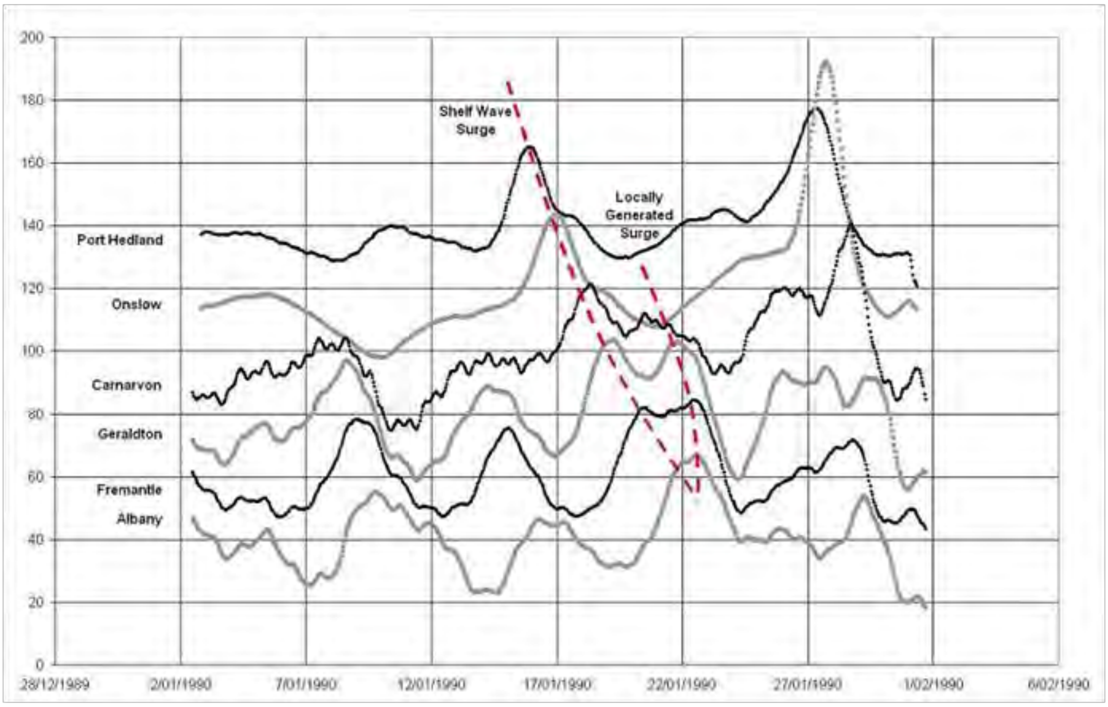


Figure 4-19: Shelf Wave Interaction with Locally Generated Surge

4.4.2.5. Mean Sea Level Variations

The 30-day and annual running means of water levels indicates two significant sources of slowly varying sea level fluctuations, at seasonal and inter-annual time scales (Figure 4-20). A relative sea level rise of 1.7 mm/year has previously been estimated from the Carnarvon long-term record from 1966-2003 (Damara WA 2008), although it is noted that the trend for any time period is strongly affected by inter-annual fluctuations, and therefore should be interpreted with caution. Also, the tide gauge location in Carnarvon was shifted in 1973, which may provide some uncertainty in the estimate of relative sea level rise.

The seasonal variation at Carnarvon averages 0.2m with a maximum in June and minimum in October largely attributed to changes in the strength of the Leeuwin Current and movement of regional atmospheric pressure belts (Pattiaratchi & Buchan 1991; Damara WA 2008; Pattiaratchi & Eliot 2008).

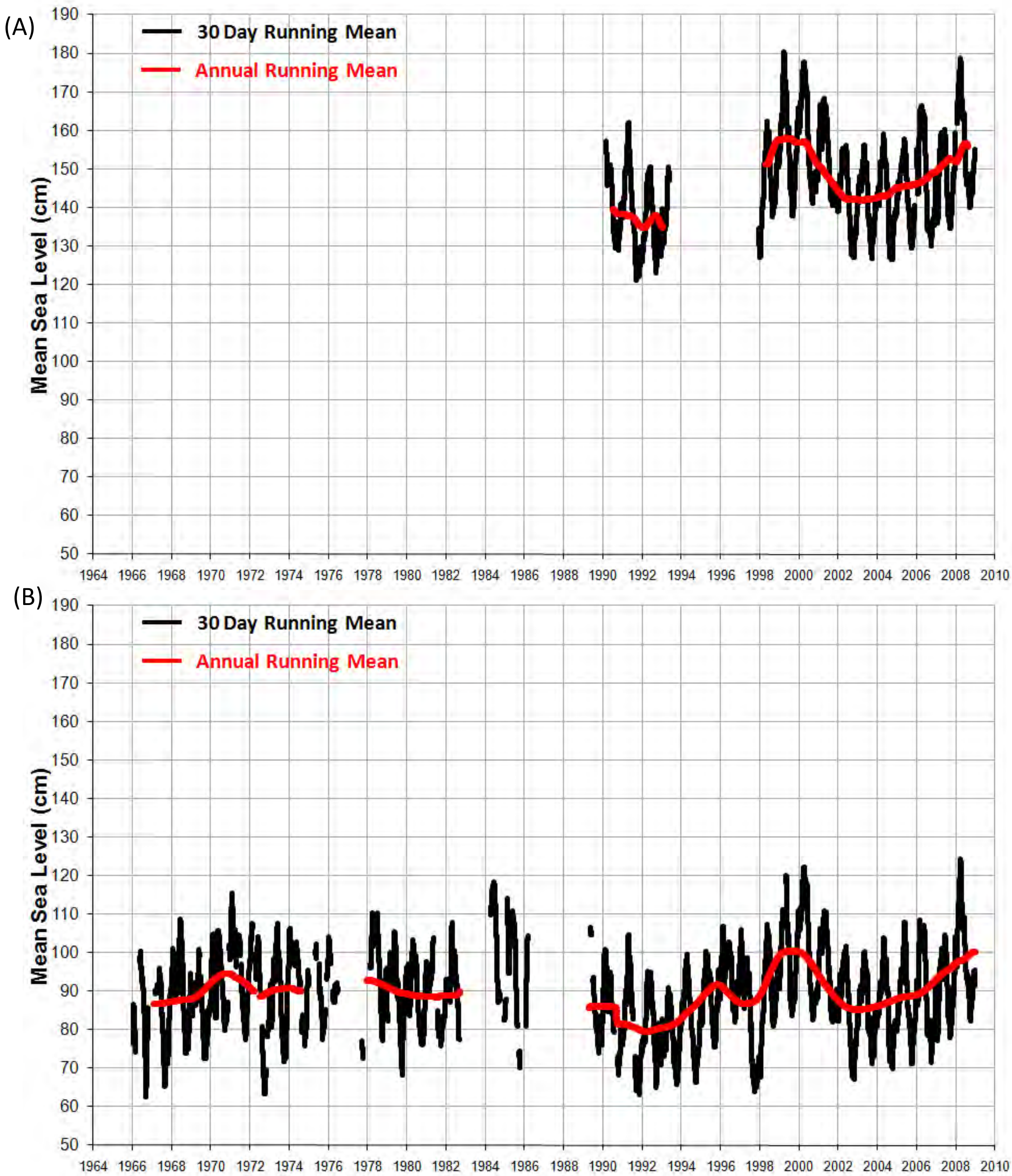


Figure 4-20: 30-Day and Annual Running Mean Sea Level (A) Exmouth (1990-1993 & 1997-2008) and (B) Carnarvon (1966-1976, 1978-1982, 1984-1986 & 1989-2008)

The inter-annual relationship between mean sea level and climate fluctuations is suggested by a strong correlation between annual average water level and SOI - the Southern Oscillation Index (Pattiaratchi & Buchan 1991). The SOI is determined by the barometric pressure difference between Darwin and Hawaii, and has been demonstrated as a reasonable indicator of El Nino or La Nina climatic conditions. The sea level relationship to SOI indicated by Figure 4-21 occurs along the entire Western Australian coast (Pariwono *et al.* 1986; Pattiaratchi & Buchan 1991; Feng *et al.* 2004).

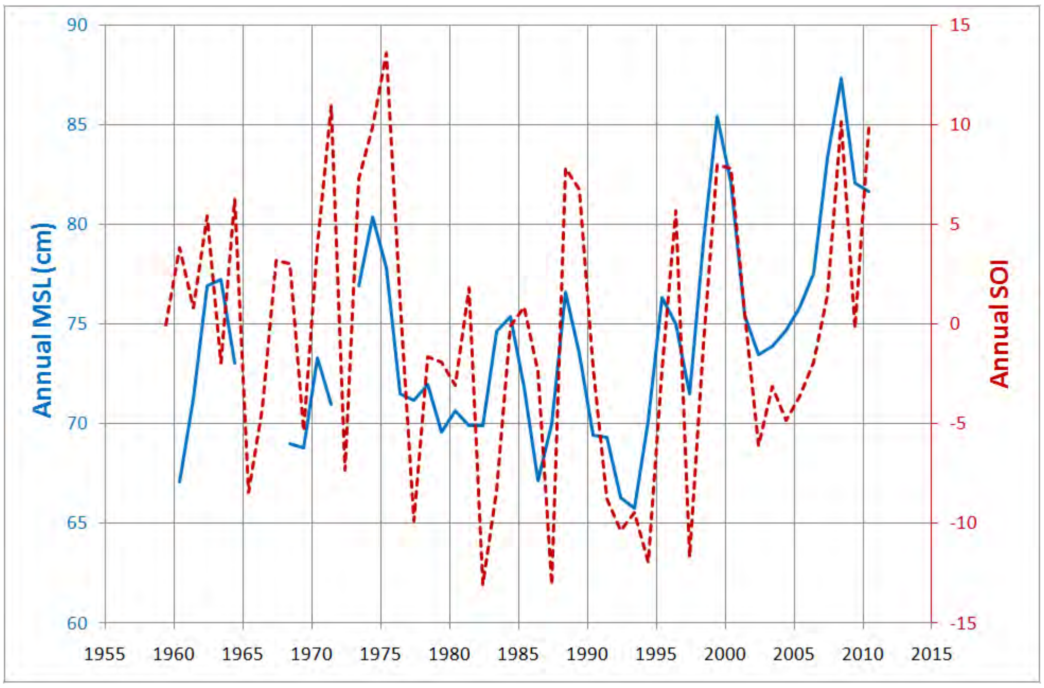


Figure 4-21: Correspondence between the Annual Means of Fremantle Mean Sea Level and SOI (1960-2010)

4.4.3. Waves

Wave measurements in the Gascoyne have been historically collected by Federal and State government agencies, including observations at the major ports and other locations where major coastal facilities were planned. These measurements have generally been sporadic in nature, with comparatively short term deployments of days to four years and have often been used for analysis of extreme wave conditions for the purpose of design.

From 1993, a series of permanent offshore waverider buoy installations have been progressively undertaken to provide a regional description of the wave climate in the southwest. In 2006, this extended north to the Gascoyne with a directional waverider buoy installed at Exmouth providing offshore wave measurements most relevant to the Gascoyne coast (Figure 4-1; Table 4-12). Observations from the wave rider buoy are illustrated in Figure 4-22.

Table 4-12: Wave Observations at Exmouth (Source: DoT website)

Station	Location	Lat. (S)	Long. (E)	Depth (m)	Installed	Removed
52	Exmouth	21°41'58"	114°05'55"	54	3/10/2006	Current

Further to this dataset, a number of analyses of waves have been conducted for the purpose of small craft facilities at Exmouth (Maunsell & Partners 1981; Riedel & Byrne 1986; Steedman & Russell 1986; Steedman 1987; Coastal Information & Engineering Services 1996; and Egis Consulting 1999a). The findings of these studies are summarised and reviewed in Damara WA (2006c).

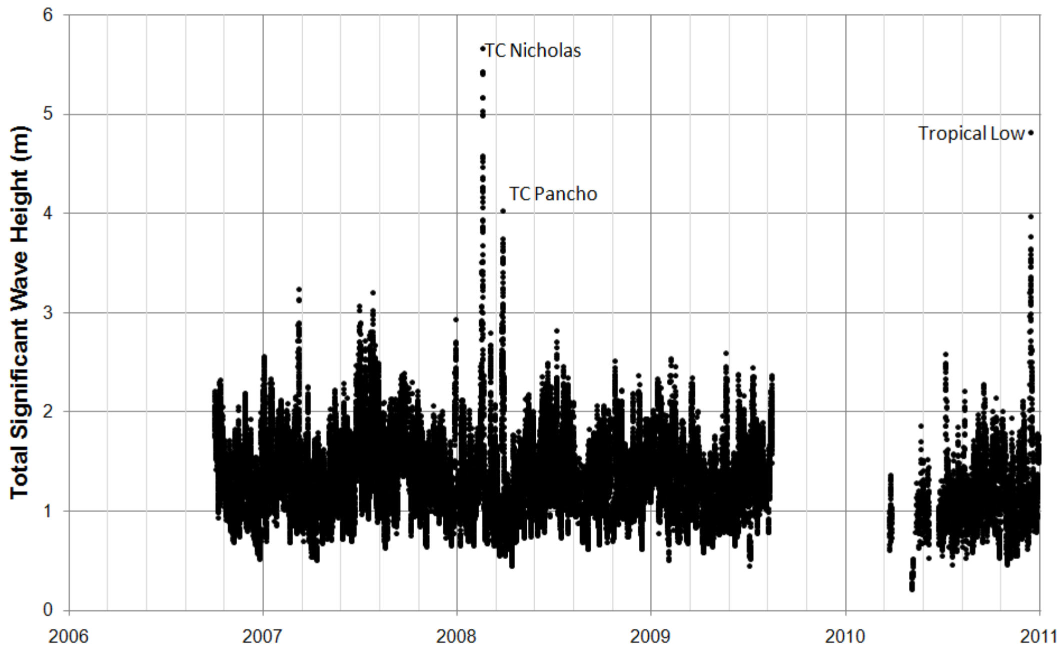


Figure 4-22: Exmouth Wave Heights from 2006-2010
(Source: Department of Transport)
Note: The data gaps in 2010 were due to a communication problems with the buoy

The Exmouth directional waverider buoy is the most relevant wave observations to the Gascoyne coast (Table 4-12). The offshore wave heights measured by the wave rider buoy are illustrated in Figure 4-22 and had a median wave height of 1.30 and 99th percentile of 2.43m (Table 4-13). The observations show seasonal and inter-annual variability evident with slightly higher ambient conditions in winter and peak winter wave heights in 2007 and peak summer wave heights in 2008. Occasional extreme events occurred during the summer months, with wave heights exceeding 4m three occasions, during TC Nicholas in February 2008 (5.66m), TC Pancho in March 2008 (4.02m) and a tropical low in December 2010 (4.81m). Mid-latitude depressions generated wave heights greater than 3m twice on two different occasions during July 2007 (3.07m and 3.20m). Given the extreme nature of cyclonic events and the identification of a high level of inter-annual variability at sites with more than one or two years of record (Riedel & Trajer 1978; Li *et al.* 2009), it is suggested that an extended period of record needs to be used when interpreting wave conditions.

Table 4-13: Median and 1% Significant Wave Heights

Location	Depth	Period	Median H_s (m)	1% H_s (m)
Exmouth	52m	October 2006 to August 2009	1.32	2.42

A cross plot of the significant wave height and peak wave period for the Exmouth observations demonstrate a broad spectral scatter (Figure 4-23). Waves above the 99th percentile of significant wave height of 2.43m occurred for peak periods of 6 to 18 seconds. This suggests a range of spatial scales over which waves are generated. The highest wave conditions are typically associated with peak periods of 10 to 13 seconds, while locally generated waves, are affected by wave steepness, forming the linear ‘front’ of the plot.

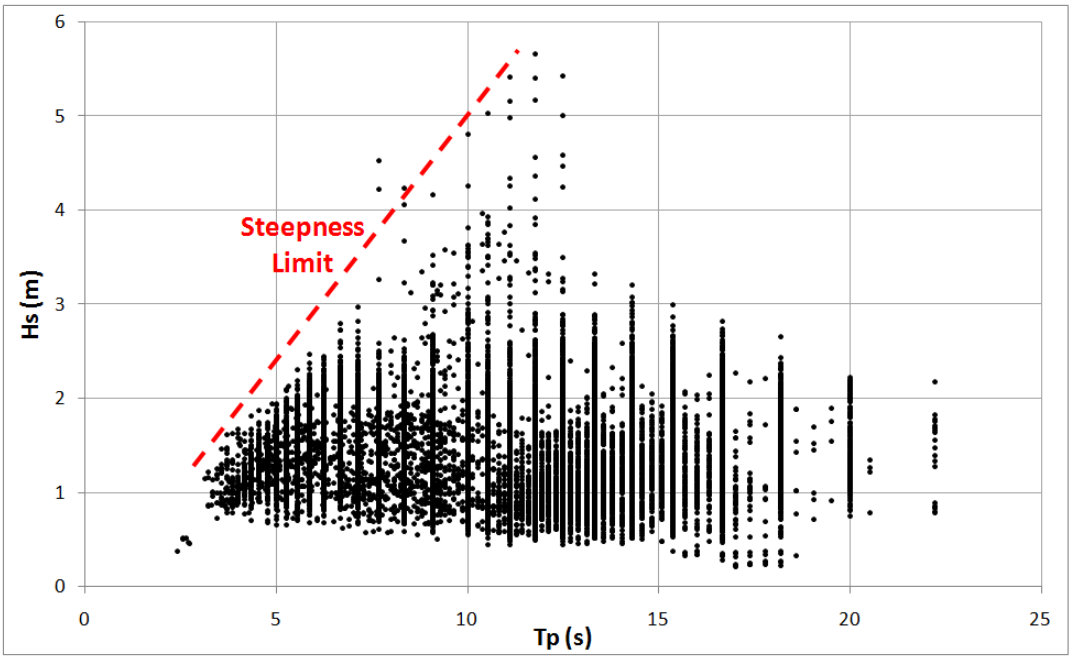


Figure 4-23: Wave Height and Period Exmouth (2006-2009)

The directional variation in wave heights between sites is considered using the directional sea and swell wave record for 2008 (Figure 4-24). The offshore swell direction is dominated by a relatively narrow directional band from the south-west to west, understood to be related to Indian Ocean swells. A greater directional range under cyclonic conditions is evident by swell wave heights greater than 2.5m recorded during TC Nicholas and TC Pancho. Waves generated locally by winds display a greater direction range owing partially to the bimodal sea-breeze structure in the lee of Cape Range. Locally generated waves greater than 2m are restricted to between 225°N and 45°N while waves from 45°N to 225°N are largely restricted below 2m.

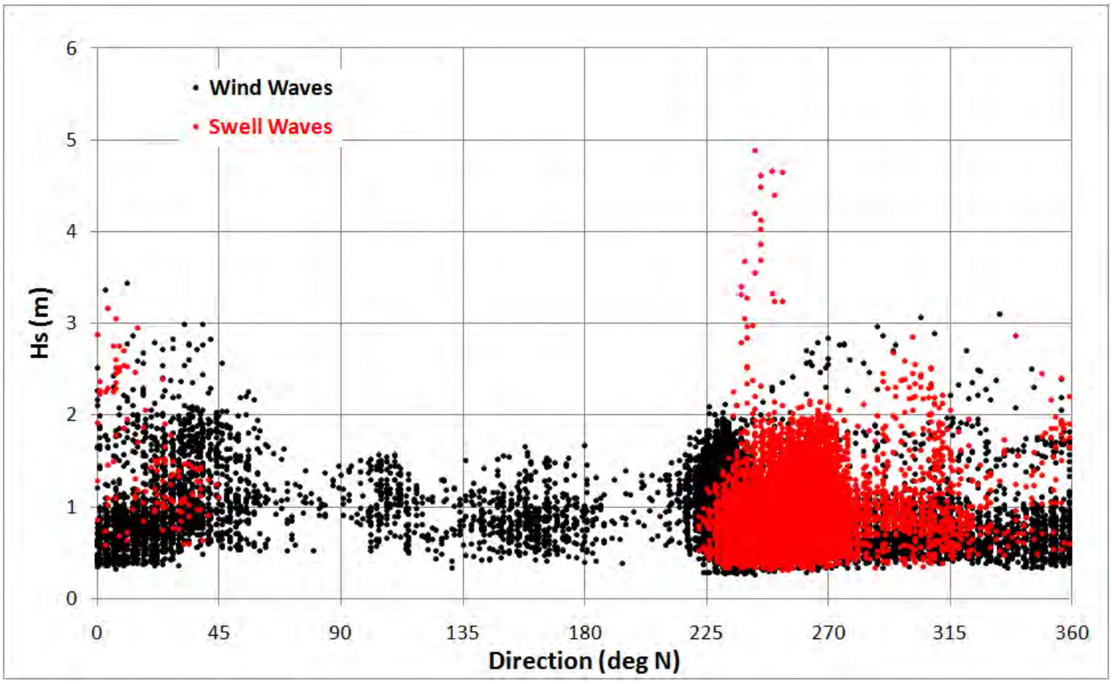


Figure 4-24: Wave Height and Direction for Exmouth for 2008

The seasonal distribution of wave heights recorded at Exmouth shows a peak in July associated with the stronger influence of swell from the southern Indian Ocean, while wave heights were lowest during April (Figure 4-25). Extreme events associated with the passage of tropical systems during February and March is shown by the peak in the 99th percentile.

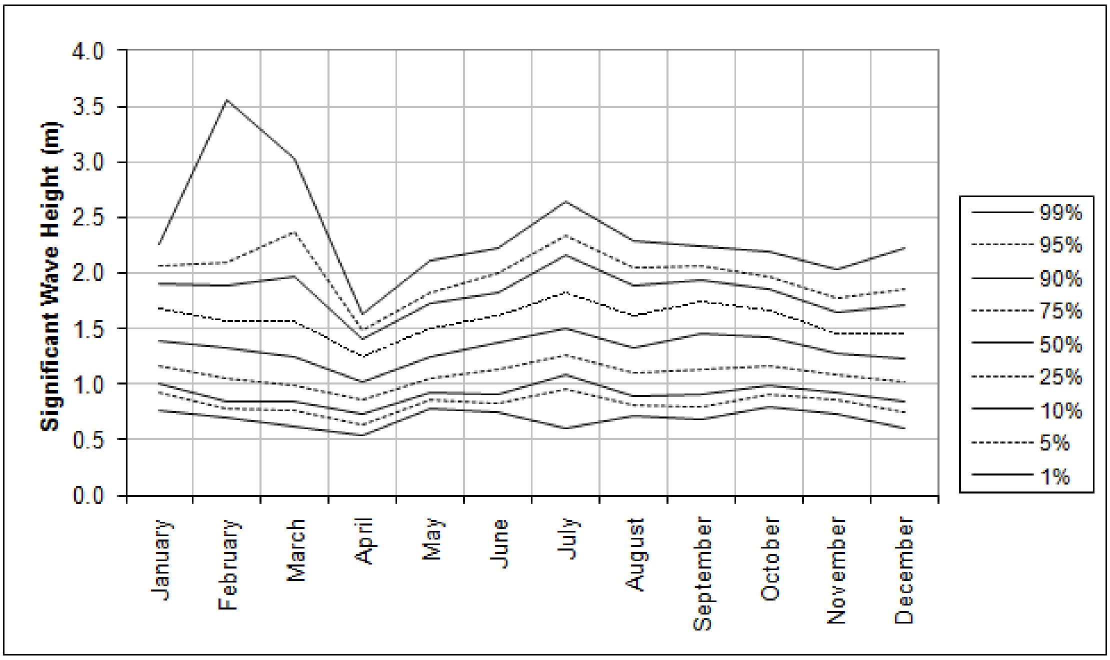


Figure 4-25: Seasonal Distribution of Wave Heights for Exmouth (2006-2009)

The varied aspect, shelf, gulf/bay and reef structure of the coast, in the context of the transition in forcing mechanisms, restricts the ability to represent the Gascoyne area using individual datasets (Section 4.2.3). Wave conditions are strongly modulated by water levels due to depth limited wave breaking and influence of refraction across the inner shelf. Local measurements at any site are required to resolve the wave forcing. A number of available short-term datasets have been collected across the Gascoyne coast.

Waves were recorded from 21 December 2004 to 30 March 2005 at Coral Bay, simultaneous with currents and water levels to facilitate the design of a boat launching facility by the Department for Planning and Infrastructure (Damara WA 2006a). The waves are not included in this report as they were not presented against longer-term datasets. Information on waves at Coral Bay is further discussed within Hearn *et al.* (1986), for the design of the proposed Coral Coast Resort (Port & Harbour Consultants 1989; Steedman Science & Engineering 1989; MP. Rogers & Associates 1994), for the design of the Coral Bay boating facility (CMPS&F 1997; Egis Consulting 1999c; DAL Science & Engineering 2002; Damara WA 2003; Department for Planning & Infrastructure 2005b) and in consideration of wave runup associated with storm surge at Coral Bay (GEMS 2005b).

Wave behaviour across areas of the Ningaloo Reef have been investigated by Hearn *et al.* (1986) and under government programs such as SRFME, the Western Australian Marine Science Institution (WAMSI) Node 3 Ningaloo Research Program and by the Australian Institute of Marine Sciences (Lowe *et al.* 2005; Brinkman *et al.* 2007; Taebi *et al.* 2011).

Further wave measurements have been recorded at locations within Shark Bay, Ningaloo Reef and Exmouth Gulf. These datasets are not considered within this report as they are relatively short deployments. These include:

Shark Bay:

- Visual assessment of wind waves in the 1960s used to investigate currents in Shark Bay and their effect on sedimentary environments by Logan & Cebulski (1970).

Ningaloo Reef:

- Four days of measurements in 10m depth at Cape Cuvier in July 1988 (Rice & Trenaman 1990; Hamilton 1997).
- Six weeks (April-May 2006) of measurements at nine locations along 4 km of coast within Sandy Bay in conjunction with a suite of other measurements (Brinkman *et al.* 2007; Taebi *et al.* 2011).
- Short-term measurements on the Tantabiddi moorings at 50m and 100m depths in March to May 1999 (including TC Vance), 2002 to 2003, 2007 and 2009 (Brinkman *et al.* 2007; AIMS 2008).
- Measurements from May to November 1988 at Ningaloo in 47m water depth (Department of Transport website).
- Measurements from December 2004 to March 2005 in 20m depth offshore of Coral Bay (Department of Transport website; Damara WA 2006a).
- Inshore wave measurements for five days June 2004 at approximately 2-3m and 5-7m depths in Coral Bay to investigate wave breaking across the reef (DPI 2005b).
- One month of measurements from August to September 2008 recorded at 32m depth offshore of Point Cloates (Brooke *et al.* 2009).
- Two weeks of measurements collected by the Australian Institute of Marine Sciences from November to December 1997 approximately 3 km southwest of Vlamingh Head, in conjunction with water level and current measurements. Wave measurements were conducted at six locations at different times, with five on the reef and one inshore of the reef (Brinkman 1998; Massel & Brinkman 1999).

Exmouth Gulf

- Measurements collected by the Australian Institute of Marine Sciences within Exmouth Gulf focused from 1994 to 1996 and included one wave measurement approximately 6 km east of Point Murat (AIMS 1997b; Massel & Brinkman 1997; Scott 1998; Verspecht 2002; Heyward *et al.* 2006).
- Measurements from November 1988 to May 1991 at Exmouth Town Beach in 10m water (Department of Transport website).

4.4.4. Currents

Current measurements and investigations have focused on Shark Bay, Ningaloo Marine Park and Exmouth Gulf.

Investigations on circulation within Shark Bay have included measurements of currents in the 1960s by Logan & Cebulski (1970), satellite information (Pearce & Pattiaratchi 1997; Pattiaratchi 2008) and numerical modelling by Burling (1998), Burling *et al.* (2003) and Nahas *et al.* (2003, 2005), with further modelling in progress by Hetzel and Pattiaratchi. Investigations of currents beyond Shark Bay have been conducted by James *et al.* (1999) and

Woo *et al.* (2006b). Woo *et al.* (2006b) collected boat based measurements for a number of transects offshore, along the length of the Gascoyne coast.

D'Adamo & Simpson (2001) summarise the oceanographic investigations at Ningaloo Reef prior to 2000. Site specific current measurements within the Ningaloo area have been conducted at Tantabiddi mooring (Brinkman *et al.* 2007; Lowe *et al.* 2010), Winderabandi Point and Turquoise Bay (Sanderson 2000), Sandy Bay (Brinkman *et al.* 2007; Taebi *et al.* 2011), Point Cloates (Woo *et al.* 2006a, b; Brooke *et al.* 2009) and for investigations related to Coral Bay (Hearn *et al.* 1986; MP Rogers & Associates 1994; Damara WA 2003, 2006d).

Heyward *et al.* (2006) summarise the measurements and modelling within the Exmouth Gulf in the 1990s. Investigations were conducted by the Australian Institute of Marine Sciences and beyond the gulf by the Defence Science and Technology Organisation (AIMS 1997b; Massel et al 1997; Scott 1998; Verspecht 2002). Numerical modelling of Exmouth Gulf currents and water levels has been conducted by WorleyParsons (2005) for the proposed Yannarie Solar Salt port operations.

4.4.5. Hydrology

The hydrologic network is gauged and monitored by the Department of Water with rainfall monitored by the Bureau of Meteorology. The gauging stations used herein are listed in Table 4-14 and labelled in Figure 4-1. Information is included on the Murchison, Wooramel and Gascoyne Rivers, with some discussion of the ephemeral creeks in Exmouth. The rivers may flow in summer or winter with the majority of rainfall occurring in May to July and January to March (Figure 4-26; Section 4.2.1). The behaviour of the rivers and contribution to the coastal processes and vulnerability are included in Sections 4.2.5, 4.3.6 and 4.3.7.

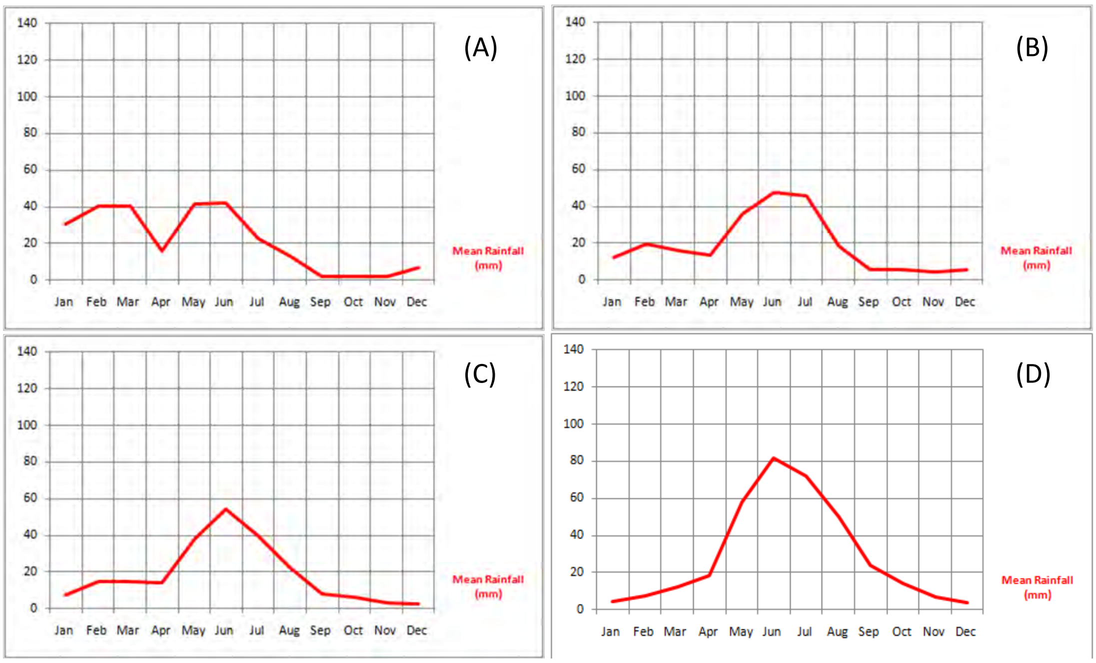


Figure 4-26: Mean Monthly Rainfall
(A) Learmonth, (B) Carnarvon; (C) Denham and (D) Kalbarri
(Source: Bureau of Meteorology)

Table 4-14: Rainfall and River Discharge Observations Incorporated for the Gascoyne Coast Note: The Lyndon and Minilya Rivers discharge into Lake MacLeod and are not considered. (Source: Bureau of Meteorology and Department of Water)

Location	Station	Lat. (S)	Long. (E)	Data	Installed	Distance Upstream from mouth
Learmonth/Exmouth						
Learmonth Airport	5007	22.241°	114.097°	Rainfall	1945	N/A
Exmouth Town	5051	21.930°	114.127°	Rainfall	1968	N/A
Vlamingh Head	5024	21.807°	114.107°	Rainfall	1913-1994	
Gascoyne River						
Carnarvon Airport	6011	24.888°	113.670°	Rainfall	1945	N/A
Mount Phillip	7058	24.400°	116.308°	Rainfall	1912	N/A
Nine Mile Bridge	704139	24.828°	113.769°	Streamflow	1957	17km
Wooramel River						
Denham	6044	25.926°	113.532°	Rainfall	1893	N/A
Carey Downs	6010	25.611°	115.463°	Rainfall	1911	N/A
Steadmans	703002	25.756°	114.278°	Streamflow	1993	16km
Meedo Pool	703001	25.738°	115.113°	Streamflow	1973	140km
Murchison River						
Kalbarri	8251	30.308°	114.165°	Rainfall	1970	N/A
Sherwood	7078	26.560°	118.540°	Rainfall	1926	N/A
Emu Springs	702001	27.855°	114.546°	Streamflow	1967	95km

4.4.5.1. Murchison River

The Murchison River catchment is 86,777 km^2 above the Emu Springs gauging station, located approximately 95 km upstream of the Murchison River mouth at Kalbarri (Figure 1-1; Figure 4-9). The total catchment area of 91,254 km^2 extends 550 km inland of the mouth (WRC 1997; Magee 2009). The river flows largely through sandstones, greenstone and granitoids (Hocking *et al.* 1982; Hocking 1991; Johnson & Commander 2006). Upstream of the mouth and initial dune field to the north, alluvial flats of approximately 1km width are adjacent to Sandstone deposits. The river mouth location is controlled by Oyster Reef, and further limestone outcropping to the south, with the dunes to the north of the mouth and the spit at Chinaman's Beach susceptible to removal during large flood events (Bailey 2005). The river discharges to a naturally wave-dominated delta, with the bar at the mouth permanently kept open by maintenance dredging (Landvision& UWA 2001). The tidal influence extends 12-20 km upstream of the mouth (Bailey 2005 after Hesp 1984).

The coastal (Kalbarri) and inland (Sherwood) monthly rainfall is presented in Figure 4-27, along with the peak monthly discharge for Emu Springs. Station locations are listed in Table 4-14 and labelled in Figure 4-1. The ten maximum recorded flows at the Emu Springs gauging station are presented in Table 4-15, with the maximum recorded event of 1,789 m^{3}s^{-1} in March 2006 associated with rainfall from ex-TC Emma falling on a saturated catchment. Major floods were reported in 1926, 1960, 1974, 1975, 1980, 1989, 1992, 1995 and 2000 (Department of Agriculture 2005; Bailey 2005; Bureau of Meteorology 1998, 2006), with additional floods in 2006 (TC Emma) and 2011 (TC Dianne).

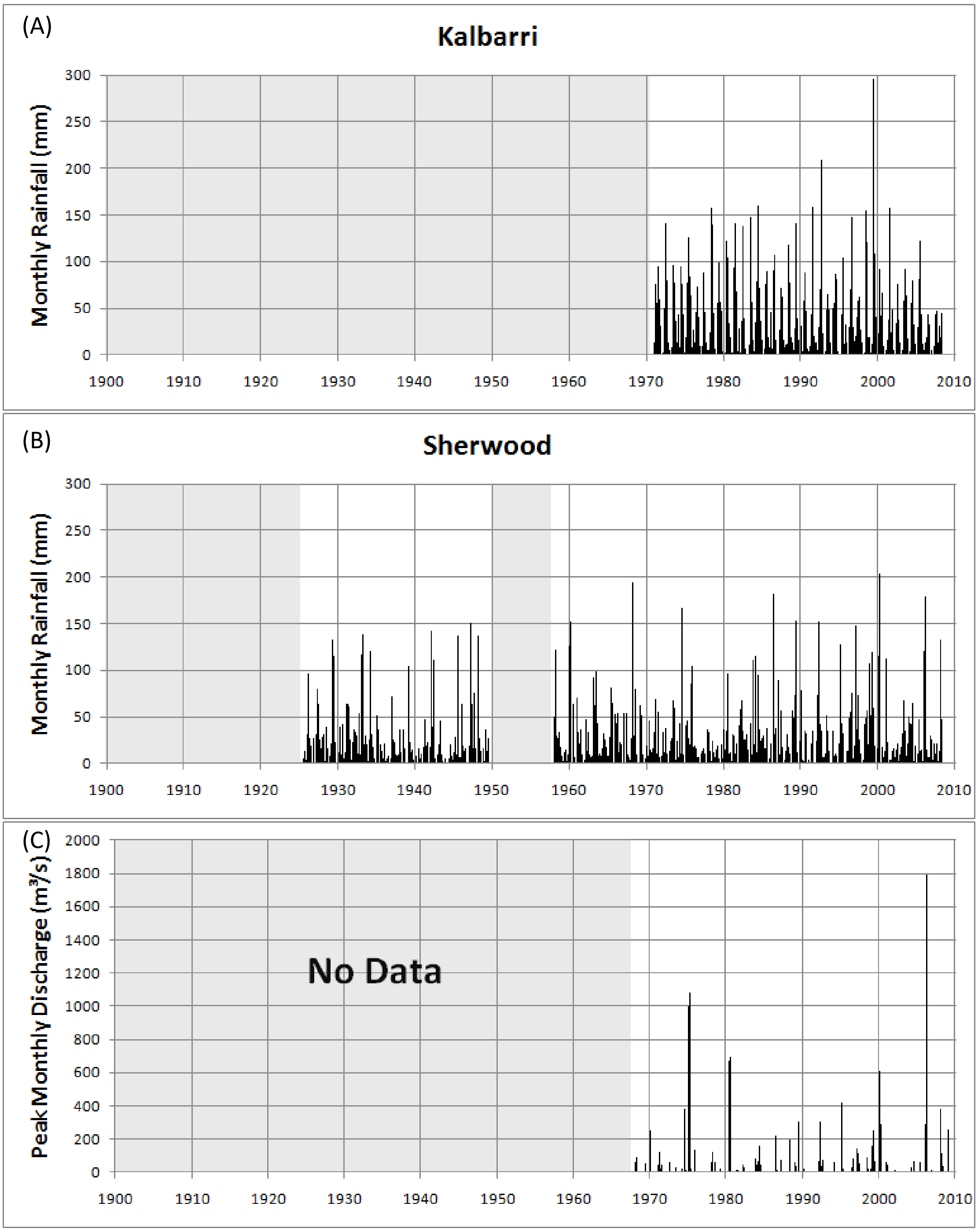


Figure 4-27: Rainfall at Selected Locations and Discharge for the Murchison River (A) Coastal Station at Kalbarri, (B) Inland Station at Sherwood and (C) Peak Monthly Discharge at Emu Springs approximately 95 km upstream of the Murchison River mouth (Source: Bureau of Meteorology and Department of Water)

The Department of Water surveyed the peak flood levels for the March 2006 event, which corresponded to an approximately 30 to 50 year Annual Recurrence Interval (ARI) event (Simon Rodgers, Department of Water, *pers. comm.*)

River flows are typically intermittent, with episodic flows in flood events sustained for long periods following heavy rainfall (Laws 1992). The ten maximum discharge events occurred during January to March, associated with tropical lows or tropical cyclones, and a succession of northwest cloudband events during the cooler months of May to July or flash flooding associated with thunderstorms (Bureau of Meteorology 1998; Figure 4-27C; Table 4-15).

Landforms at the river mouth contain sediment that may be mobilised during significant flood events. These landforms in the estuary, sand spit, bar and dune blowouts contain a mixture of sediments of marine and terrestrial origin (Bailey 2005). The behaviour of the river mouth in relation to the river and coastal littoral drift has been investigated by Bailey (2005; following DMH 1989 and CIES 1996) in relation to the annual dredge volumes required to maintain a navigable entrance. These studies suggest that the river mouth landforms are mobilised during large flows, nett littoral drift estimates are approximately 27,000-33,000 m^3/yr and approximately 20,000-35,000 m^3/yr of sediment is dredged from the channel (DMH 1989; Bailey 2005). Following a significant flood event, it is likely that a large proportion of the nett littoral drift will be entrained into the flood scoured areas.

Table 4-15: Ten Largest Peak Discharge Events for the Murchison River (1967-2009)

Year	Month	Peak Discharge (m^3/s)	Event
2006	March	1,789	TC Emma on saturated catchment
1975	March	1,080	TC Trixie plus subsequent rainfall
1975	February	998.6	TC Trixie
1980	July	694	Deep low
1980	June	672.1	Deep low
2000	March	611.8	TC Steve
1995	March	416.6	TC Bobby
2008	February	381.1	TC Melanie
1975	July	376.6	
1975	April	347.5	TC Beverley

4.4.5.2. Wooramel River

The total catchment area of the Wooramel River basin is approximately 41,000 km^2 extending 350 km inland of the mouth located at Herald Loop, Shark Bay (WRC 1998a; Figure 1-1; Figure 4-9). The mouth of the main river, the Wooramel, flows through pastoral lands into the littoral land system (Figure C - 8 and Figure C - 9 in Appendix C), discharging to a sheltered delta on the outwash plains and tidal flats of Wooramel Bank (Butcher *et al.* 1984). The Wooramel delta was previously more active and is now largely comprised of tidal flats, fronted by spits, with mangroves and algal mats. Tidal creeks appear to have originated as, and are primarily maintained by, the surface drainage during floodwater discharge.

The Wooramel River was first gauged in 1973 at Meedo Pool, approximately 140 km upstream of the mouth, with a subsequent station at Steadmans in 1993, approximately 16 km upstream of the mouth. The Meedo Pool station ceased recording in 2001. These stations are both included in consideration of the longer record. The catchment is 7,826 km^2 above Meedo Pool and 13,756 km^2 above Steadmans (Department of Water website).

The coastal (Denham) and inland (Carey Downs) monthly rainfall is presented in Figure 4-28, along with the peak monthly discharge for Meedo Pool and Steadmans gauging stations.

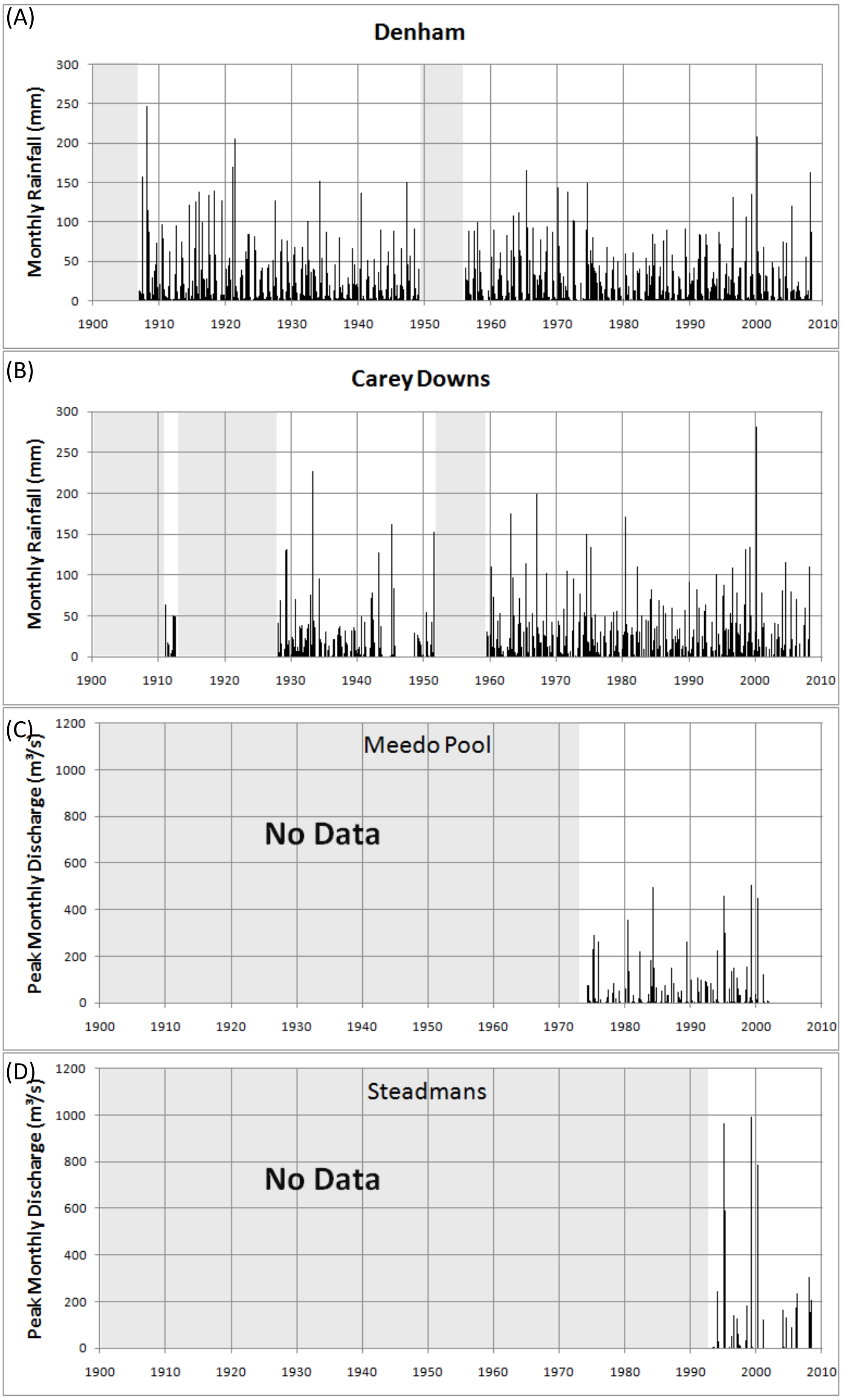


Figure 4-28: Rainfall at Selected Locations and Discharge for the Wooramel River (A) Coastal Station at Denham, (B) Inland Station at Carey Downs and (C) Peak Monthly Discharge at Meedo Pool (D) Peak Monthly Discharge at Steadmans. Steadmans and Meedo Pool are approximately 16 km and 140 km upstream of the river mouth (Source: Bureau of Meteorology and Department of Water)

Station locations are listed in Table 4-14 and labelled in Figure 4-1. The seven to eight maximum recorded flows at the gauging stations are presented in Table 4-16, with the maximum recorded event at both stations in March 1999 associated with rainfall from TC Vance. This generated flows of 993 m^3s^{-1} at Steadmans and 505 m^3s^{-1} at Meedo Pool. Other significant flows since 1973 were largely associated with tropical cyclones and tropical lows in 1975, 1995, 2000, 2006 and 2008. One of the significant flows occurred during winter associated with a Northwest cloudband connected to a deep low. A flood in January 1967, associated with TC Elsie, washed away parts of the Wooramel Bridge (BoM 1998).

Table 4-16: Ten Largest Peak Discharge Events for the Wooramel River
Note: Numbers in brackets are a station rank ascending from 1, the highest recorded peak

Year	Month	Steadmans Peak Discharge 1993-2009 (m^3/s)	Meedo Pool Peak Discharge 1973-2001 (m^3/s)	Event
1999	March	993.2 (1)	505.4 (1)	TC Vance
1995	February	965.5 (2)	459 (3)	TC Bobby
2000	March	784.9 (3)	449.5 (4)	TC Steve
1995	March	589 (4)	300.1 (6)	TC Bobby
1994	February	245.7 (6)	226.2 (8)	Tropical low thunderstorms
1984	March		497.3 (2)	
2008	February	303.6 (5)		TC Melanie
2006	March	236.3 (7)		TC Emma on saturated catchment
1980	June		354.3 (5)	NW cloudband and deep low, on saturated catchment
1975	April		292.8 (7)	TC Beverley

4.4.5.3. Gascoyne River

The Gascoyne River discharges into an active river-dominated delta, with reworking of sediments by local metocean forcing. The Gascoyne River provides a significant source of sediment to the coast from Babbage Island spit at Carnarvon towards Point Quobba. Although it can remain dry for extended periods of time, following intense rainfall, the Gascoyne can flood for weeks, carrying a massive sediment load, much of which drops out of suspension near to the river mouth. This sediment supply is readily available for transport both north and south from the entrance. The supply of sediment, flooding and reworking of sediments influences alluvial and coastal low-lying landforms of tidal flats, mangal flats, the Gascoyne delta plain, alluvial plains, strandplains, river channels, foresdunes, spits and sand islands (Figure G-7 and Figure G-8 in Appendix G). Although the offshore wave conditions suggest a general northwards movement, the aspect and curvature of Babbage Island resists northwards sediment transport, encouraging a feed of sediment from the river mouth towards the spit (GEMS 2009).

High vulnerability of the area adjacent to the Gascoyne River is related to the high risk of tropical cyclonic inundation and overtopping; river flooding and altered sediment supply. River flooding may cause river channel migration or bank retreat and modify sediment supply to the adjacent coast. Flooding has a high risk of causing landform inundation (including washover), migration, deflation, erosion or accretion.

Landforms at the river mouth contain sediment that may be mobilised during significant flood events. Following a significant flood event, it is likely that a large proportion of the nett littoral drift will be entrained into the flood scoured areas.

The Gascoyne River catchment is 74,432 km^2 above the Nine Mile Bridge gauging station, located approximately 17 km upstream of the Gascoyne River mouth at Carnarvon (Figure 1-1; Figure 4-9; Department of Water website). The total catchment area of 78,800 km^2 extends 780 km inland of the mouth, with the Gascoyne River as the dominant river (WRC 1998a). River channel widths are up to 1 km in areas with a maximum depth of 7 m (WRC 1998a). A major tributary of the Gascoyne River is the Lyons River, joining just to the west of Gascoyne Junction approximately 150 km upstream of the mouth.

Stream gauging in the Gascoyne River Basin commenced on the Gascoyne River at Nine Mile Bridge in 1957. There were seven stream gauging stations in the Gascoyne River Basin in 1998, with five operating presently (WRC 1998a; BoM 2011). The four additional stations to Nine Mile Bridge are Jimba, Fishy Pool, Yinnethara Crossing and Lyons River Crossing (Department of Water website).

The coastal (Carnarvon) and inland (Mount Phillip) monthly rainfall is presented in Figure 4-29, along with the peak monthly discharge for Nine Mile Bridge. Station locations are listed in Table 4-14 and labelled in Figure 4-1. The ten maximum recorded flows at the Nine Mile Bridge gauging station are presented in Table 4-17 to the end of 2009, excluding the December 2010 flood event (BoM 2011). The maximum recorded event of 6,033 m^3s^{-1} in February 1960 was associated with rainfall from a decaying tropical cyclone and a number of tropical depressions (BoM 1998). Eleven major floods were reported from 1883 to 1957 when recording started, with additional floods in 1960, 1961, 1965, 1974, 1980, 1989, 1995, 1999, 2000, 2009 and 2010 (BoM 1998; SKM 2002; BoM 2011). The floods with the highest river stage at Nine Mile Bridge since 1951 were the 1960, 2000 and 2010 floods. The December 2010 flood had the highest river levels on record at three of the five river gauging stations (BoM 2011). A height of 7.80m was recorded at Nine Mile Bridge, higher than 7.63m in 1960 and 7.60m in 2000 (BoM 2011).

River flows may be sustained for long periods following heavy rainfall. The ten maximum discharge events occurred during January to March, associated with tropical lows or tropical cyclones, with further flooding during a succession of northwest cloud band events during the cooler months of June and July or flash flooding associated with thunderstorms (BoM 1998; Figure 4-29C; Table 4-15). The most significant flooding occurs between Gascoyne Junction where it is joined by the Lyons River and the river mouth (BoM 1998).

Information on the Gascoyne River hydrology, historical river channel and landform response and potential future response are contained in the recent *Cyclonic Inundation and Coastal Process Modelling* study (GEMS 2009), flood studies and assessments of geomorphology and geology (Johnson 1974; Hocking 1990). The most recent flood study by SKM (2002) revised flooding of the lower Gascoyne floodplain following prior investigations by PWD (1976), Water & Rivers Commission (1998b) and SKM (2002). The SKM (2002) study determined 15, 25 and 100 year floodplain and floodway models (Section 6.4.1), but did not include the December 2010 flood event.

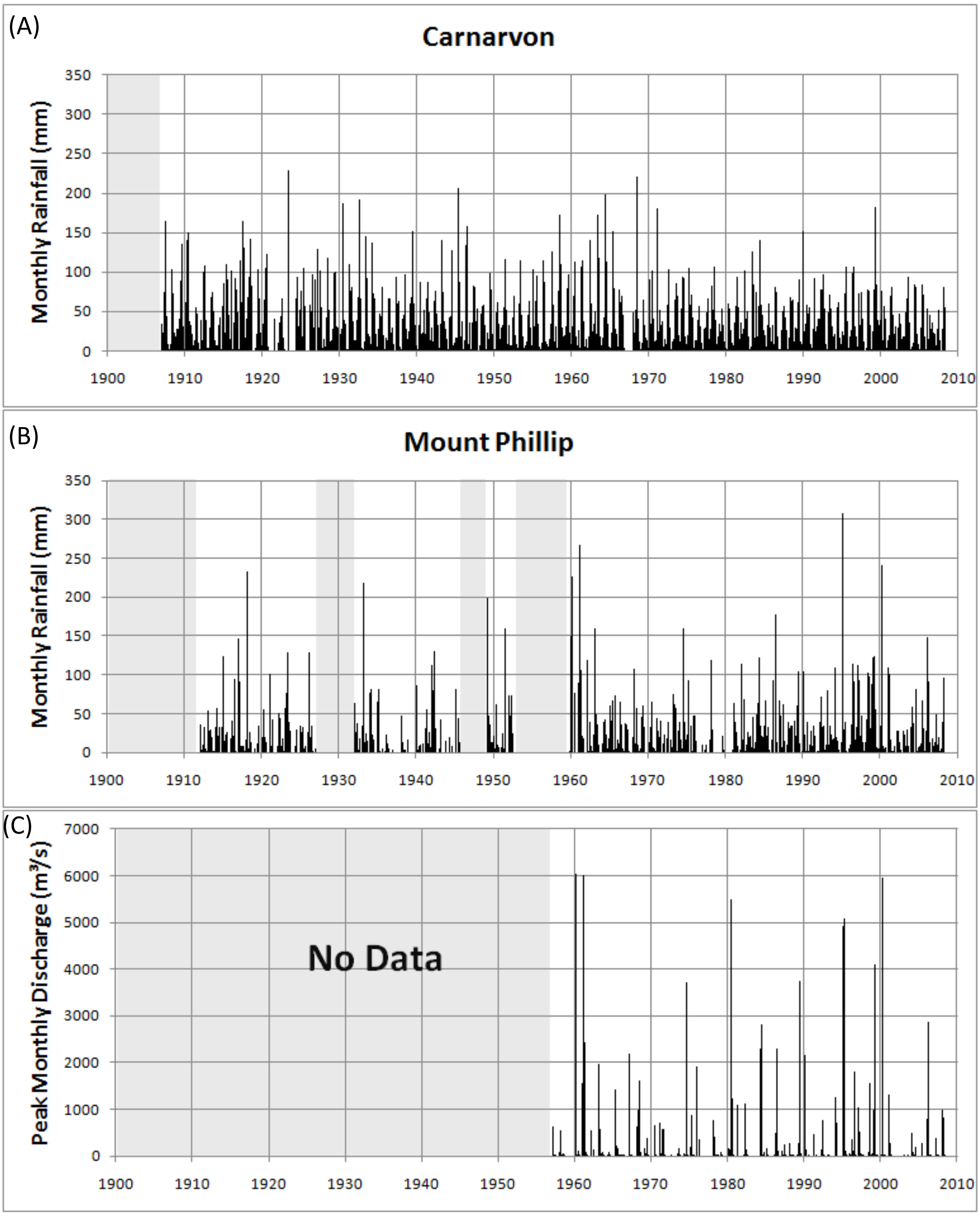


Figure 4-29: Rainfall at Selected Locations and Discharge for the Gascoyne River (A) Coastal Station at Carnarvon, (B) Inland Station at Mount Phillip and (C) Peak Monthly Discharge at Nine Mile Bridge approximately 17 km upstream of the river mouth (Source: Bureau of Meteorology and Department of Water)

The potential response to the river channel to extreme flow was reported in GEMS (2009), through determining if the channel cross-section has sufficient capacity to deliver a flood flow rate. The river level will rise and the channel will be eroded if there is insufficient capacity. The assessment used a 100 year ARI extreme flood for the stream gauging station at Nine Mile Bridge of 6,500 m^3s^{-1} (GEMS 2009). Relative expansions of depths and widths were calculated based on ratios incorporating flow rate. The maximum potential riverine response at 3km upstream of the mouth was a potential width expansion of the channel by 120 m and a potential deepening of 2.2m.

The Gascoyne River delta has been modified extensively, including construction of levees following the 1960 flood, the closure of the South Arm in 1986 using a levee at its northern end fascilitating use of the Fascine (SKM 1981b; GEMS 2009), construction of the harbour and dredge channel in 1976 along with a number of further flood structures. Further flood and surge management options have been proposed by SKM (1981b), WRC (1998), SKM (2002), DPI (2003), DPI (2004) and GEMS (2009). This includes the possible extension of the levee walls (SKM 2002; DPI 2003; DoP 2009a; GHD *In Prep*) including a possible western levee (DPI 2004). The detailed design for the recommended levees is being conducted by GHD, following recommendations by SKM (2002). Any modifications to the delta, river channels and structures have the potential to change the risk of flooding and inundation (Section 6.4.1).

Table 4-17: Ten Largest Peak Discharge Events for the Gascoyne River (1955-2009) This excludes the December 2010 flood which produced the highest river stage at Nine Mile Bridge on Record (BoM 2011)

Year	Month	Peak Discharge (m^3/s)	Event
1960	February	6,033	Decaying TC and number of depressions
1961	February	6,011	TC on 25/1 and TC on 12/2
2000	March	5,955	TC Steve
1980	June	5,493	NW cloudband and deep low, on saturated catchment
1995	March	5,070	TC Bobby
1995	February	4,925	TC Bobby
2009	January	4,897	TC Dominic
1999	March	4,107	TC Vance
1989	June	3,752	NW cloudband
1974	July	3,724	

4.4.5.4. Exmouth

Creek systems within the Gascoyne region are often ephemeral, with locally significant incised channels draining ranges or escarpments in the Trealla Land System around Alison Point; Range Land System around Cape Range, including Vlamingh Head and Exmouth (Figure 4-30); and on the peninsulas of Shark Bay. Flooding of these creeks typically occurs during high local rainfall events. The small coastal catchments of Exmouth are used as an example of creek behaviour due to available data and prior flood studies.

The ephemeral creeks at Exmouth townsite provide a risk of flooding during high rainfall events demonstrated by the flooding associated with TC Vance in March 1999 (Martens *et al.* 2000; SKM 2007), a Northwest cloudband in June 2002 (SKM 2007) and TC Pancho in March 2008 (BoM 2008). A flood study conducted by JDA Consultant Hydrologists (1999) was revised following TC Vance (Martens *et al.* 2000; JDA 2002) and the 2002 flood (SKM 2007).

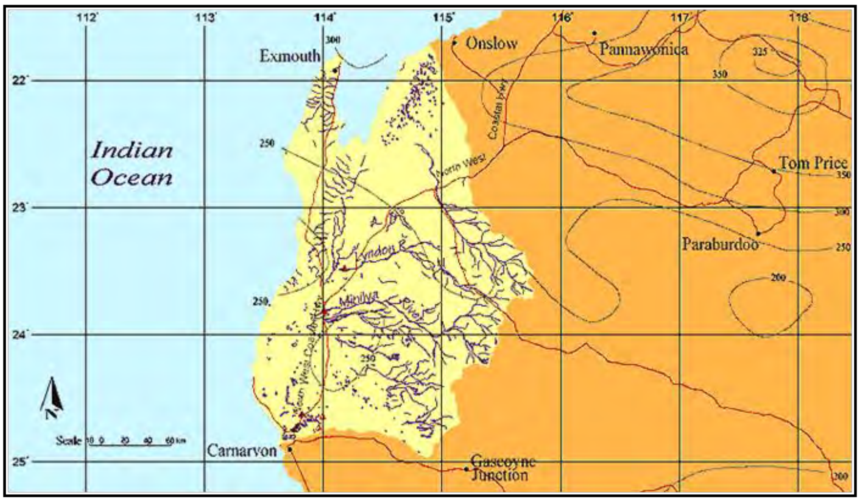


Figure 4-30: River Catchments in the Lyndon-Minilya, Yannarie and local Cape Range (Source: Department of Water)

There are six small coastal catchments in Exmouth townsite, totalling 45 km^2 (Martens *et al.* 2000; Figure 4-31). The catchments are fronted by coastal dunes formed by alongshore aeolian transport and commonly result in deltaic deposition behind the dunes (Figure G-18: Exmouth LandformsFigure G-18 in Appendix G). Inundation of flood basins and dune breakouts can occur during a significant flood, with the location of breaching influenced by areas of historic breakouts, narrow dune width and human intervention. Floodrisk maps were prepared by SKM (2007) based on floodplain modelling. However, artificial breaches in the dunes for beach access and any drainage or floodway diversions modify flood behaviour and coastal risk, which may render previous flood studies obsolete.

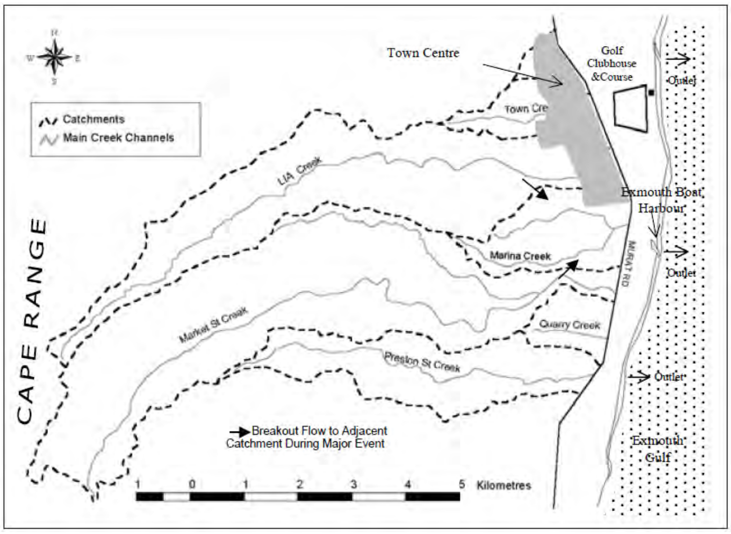


Figure 4-31: Creek Catchments Affecting Exmouth Boat Harbour (Source: Martens *et al.* 2000)

The North West Cape rainfall datasets are used as an indicator of potential rainfall due to an absence of streamflow gauging. Daily rainfall records are considered for Vlamingh Head (1913-1994), Learmonth Airport since 1945 and Exmouth Town since 1968 (Table 4-14). The potential flooding associated with each rainfall event relies on additional factors to the rainfall intensity. Runoff flooding is enhanced by sequencing of rainfall events resulting in rain falling on a saturated catchment or if the vegetation in the catchment is reduced by bushfire as occurred during TC Vance (Martens *et al.* 2000). Small coastal catchments may have direct coincidence of runoff and surge during tropical cyclone events. This may increase flood levels, flood basin holding times and modify breach locations in the coastal dunes. High risk of runoff flooding occurs after prolonged periods of negligible river flow when littoral transport closes the creek mouth breaching of the dunes. Conversely, the highest risk of coastal indundation from storm surge or tsunami is following a significant runoff flooding event when the breach channels are open.

The monthly rainfall for Learmonth Airport is presented in Figure 4-32A, with many individual daily events for Vlamingh Head, Learmonth Airport and Exmouth Town exceeding the monthly averages (Figure 4-32B). The daily totals of intense local rainfall events indicates the historic potential for flooding at Exmouth (Figure 4-32B).

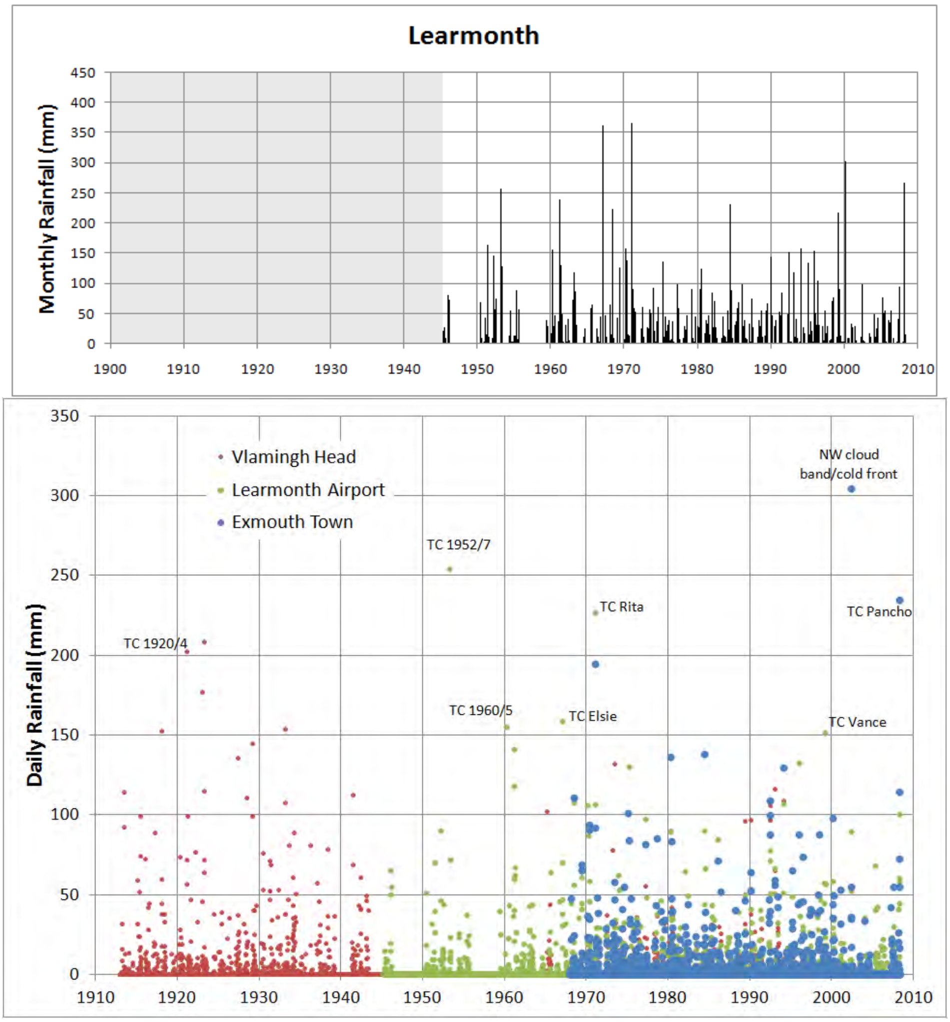


Figure 4-32: Daily Rainfall at Exmouth Stations
(A) Monthly rainfall at Learmonth Airport; and (B) Daily rainfall at Vlamingh Head (1913-1994), Learmonth Airport (1945-2008) and Exmouth Town (1968-2008).
Note: There are gaps in the datasets.
(Source: Bureau of Meteorology)

The seven maximum recorded rainfall events at the Learmonth Airport and Exmouth Town stations are are presented in Table 4-18, demonstrating the varied rainfall across small distances due to topography, coastal form and rainfall patterns. The highest 24 hour rainfall record of the three stations occurred in June 2002 at Exmouth Town gauge with 304.6mm, exceeding Exmouth's annual average (SKM 2007). This event ranked as the 19th highest event recorded at Learmonth Airport. The gauge at Exmouth Town did not record during TC Vance and was the fifth highest single day rainfall on record at Learmonth Airport.

Other significant rainfall events were largely associated with tropical cyclones and tropical lows, or during winter associated with Northwest cloudbands. The highest 24 hour rainfall record for the Gascoyne region was 412.8mm in March 1964 at Yardie Creek (BoM 1998), 50 km southwest of Exmouth, which is 108 mm more than the highest value recorded at Exmouth.

Table 4-18: Seven Largest Daily Rainfall Events for Learmonth Airport and Exmouth Town Note: Numbers in brackets are a station rank ascending from 1, the highest recorded. Numbers in grey italics are ranked lower than 7th.

Year	Month	Day	Learmonth Airport 1945-2008 24 hour rainfall (mm)	Exmouth Town 1968-2001 24 hour rainfall (mm)	Event
2002	June	4	*89.6 (19)*	304.6 (1)	NW Cloudband and front
1953	March	23	254 (1)	-	TC 1952/7
2008	March	27	*60.6 (37). Event total 263.4mm*	234.4 (2). Event total 476.4mm	TC Pancho
1971	January	25	226.6 (2) on 26th	194.8 (3) on 25th	TC Rita
1967	January	22	158.8 (3)	-	TC Elsie
1960	March	26	154.9 (4)	-	TC 1959/6
1999	March	23	151.4 (5)	Instrument error	TC Vance
1961	March	3	141 (6)	-	
1984	May	20	*90.4 (16)*	137.8 (4)	NW Cloudband and front
1980	April	20	*89.8 (18)*	136.4 (5)	
1995	December	12	132.8 (7)	*87.6 (16)*	
1994	February	22	*107 (11)*	129.6 (6)	Tropical low and thunderstorms. Rank 14th for Vlamingh Head with 109mm. Rank 1st of 208.8mm 23 March 1923
2008	March	29	*100.2 (14). Event total 263.4mm*	114.6 (7). Event total 476.4mm	TC Pancho

4.5. COASTAL CHANGE

4.5.1. Coastal Change Concepts

The coast, as the interface between the land and the sea is naturally dynamic, in response to tide, weather and climate variations. However, the nature of response varies according to the relative resistance of the coast, which is a combination of material types (geology, sediment type and presence of vegetation) and the coastal form (which may be plan form, profile, or configuration of landform elements). The factors of environmental forcing, materials and landform have considerable interaction, in which variation of one factor potentially changes the other two.

Coastal change occurs over a wide range of temporal and spatial scales. More slowly varying metocean processes provide extrinsic forcing and affect the physical structure of the coast, whereas more rapidly varying processes cause change that may have a reduced residual effect on structure when considered over an extended period but significant local effects on surficial landforms. The conceptual framework under which observed changes have been assessed commonly uses the assumption that different spatial scales will be dominated by processes acting over corresponding time scales (de Vriend *et al*. 1993; Cowell & Thom 1994). This framework is often used to justify four distinct scalar concepts when describing coastal change:

1. At the largest (geological) scales, coastal change is dominated by eustasy (sea level movements), isostasy, tectonics, lithification and occasionally vulcanology (van de Plassche 1986). These processes determine the presence of rock, and through movement of relative sea level, may relate to large movements of the coast;
2. At medium (geomorphic) scales, coastal evolution is determined by the production of mobile sediments, transfer via metocean forcing and accumulation in zones of relative shelter associated with the geologic framework of the coast. This suggests simulation of coastal change using sediment budgets tied to identification of large-scale sources, transport paths and sinks (Komar 1996; Rosati 2005) prompting the concept of equilibrium coastal alignment (van Rijn 1998);
3. Over short (planning) scales, large scale sinks and sources of material may be considered constant and shoreline fluctuations caused by storm erosion-recovery cycles may be considered almost in balance. Coastal change may be described largely by alongshore sediment transport and its variability, including spatial variation developed through changes in coastal aspect, and year-to-year metocean variations;
4. Over very short (coastal management) scales, dramatic coastal change occurs in response to weather cycles. This is most commonly represented as cross-shore transport associated with storm events and subsequent recovery during lower energy conditions (van der Meer 1988).

It is relevant to note that change may be active over all time scales simultaneously. Hence, when assessing change, care is required to ensure that the process of change is not inappropriately identified due to confined use of one or two concepts.

4.5.2. Coastal Change on the Gascoyne Coast

General Behaviour

The prevailing coastal character of the Gascoyne is inherited, with limited availability of coastal sediments. The Gascoyne River provides the major local exception, with high supply of fluvial sediment. The inherited character of the coast refers to the widespread presence of sedimentary features which sit relative to rock in such a manner that they are not directly responsive to present-day environmental forcing. Instead, these features have typically formed in response to historic conditions, often several thousand years before present, and are subsequently evolving gradually, but are resistant to moderate environmental conditions. Change largely occurs during extreme environmental conditions, and consequently there is a potential ‘tipping point’ response to climate change (Figure 4-33).

Active, inherited and fixed coastal components may all be present on a single section of coast, as illustrated by a perched dune above a rock scarp, fronted by an active beach (Figure 4-34).

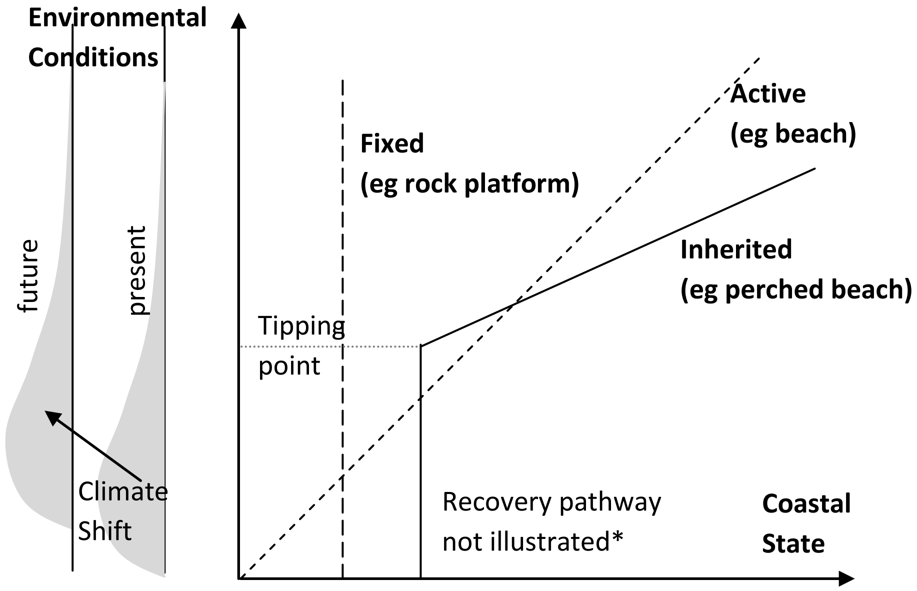


Figure 4-33: Schematic Diagram of Active, Inherited and Fixed Coast Response to Environmental Conditions
The influence of recovery is not illustrated in this diagram. For active systems, recovery may mitigate response, enabling gradual response to increasing environmental conditions.

Coastal change generally involves evolution towards a more stable configuration, albeit responding to continuously changing environmental conditions. As a consequence, the long-term configuration *often* reflects prevailing conditions, with limited gradual change except during unusual or extreme conditions, after which the coast ‘recovers’ towards the prevailing structure. However, in situations where prevailing conditions or material limits constrain recovery, the coast exhibits inherited behaviour, with the structure being a relic of previous extreme conditions. Coastal response for lower energetic conditions is generally small and often biased by the gradual ‘recovery’ trend. ‘Inherited’ behaviour is most common for systems where there is a large difference between prevailing and extreme environmental conditions, such as river channels, low energy beaches and coasts affected by tropical cyclones.

The inherited character of the Gascoyne coast is significant for the calculation of coastal setbacks:

- The relative response to moderate environmental conditions is likely to be low. Careful selection of the design event for acute erosion (S1) is required to capture the likely 100 year erosion event, with 150-year ARI representing the median likelihood extreme event over the planning horizon;

- Historic patterns of change are likely to be low (S2) as evolution is gradual, and may not reflect potential change associated with climate change tipping points;
- Geomorphic response to sea level rise rarely involves equilibrium profile shifting, therefore invalidating the use of the Bruun ratio. Allowance for response to sea level rise (S3) may need to be calculated on a case-by-case basis.

Figure 4-34: Illustration of Active, Inherited and Fixed Coastal Components

Local Behaviour

At a broad regional scale there is a paucity of detailed morphostratigraphic description and historical information describing metocean processes. Exceptions are research conducted in four areas as described in 4.2 to 4.4 above. The four areas include Ningaloo Marine Park (eg. Hearn *et al.* 1986; Sanderson 2000; D'Adamo & Simpson 2001; Collins *et al.* 2003; GEMS 2005b; Brinkman *et al.* 2007; Taebi *et al.* 2011; Collins & Twiggs 2011), the Shark Bay World Heritage Area (eg. Logan & Cebulski 1970; Read 1974; Burling *et al.* 2003; Nahas *et al.* 2005), Carnarvon as summarised in GEMS (2009) and Exmouth Gulf (eg. Steedman & Russell 1986; Brown 1988; Nott & Hubert 2005; Heyward *et al.* 2006; Twiggs & Collins 2010). The following general observations about coastal change and stability have been drawn from available information, site visits and interpretation of imagery. They are discussed at the scales of coastal change described above.

At a geological timescale features defining secondary coastal compartments provide topographic control for the formation of unconsolidated landforms. This is significant where sediment is available, and the landforms have evolved over the past 10,000 years. Several sets of landform development are of particular interest. First, three large river systems have contributed to coastal development through delta building and floodplain development; the Murchison, Wooramel and Gascoyne Rivers. The nature of their geologic inheritance, processes of change and deltaic landform responses differ for each river system. Significant floodplain development, including channel switching (avulsion) is currently apparent on the delta of the Gascoyne River. Apart from the large river systems are ephemeral creeks on the peninsulas of Shark Bay and around Cape Range. These have small catchments with intermittently flowing streams that are locally important at times of high flood discharge when they interact with coastal processes. Second, the Wooramel and Gascoyne River systems have contributed geologically to the formation of extensive outwash plains that grade to tidal flats along their seaward margins. The formation and maintenance of tidal flats, including their supratidal and subtidal components are of physical and biological significance. The significance of the former is due to their geographic extent within the region the latter due to their roles as essential life habitats. Third, barrier evolution is continuing at present, albeit slowly, as sediment is moved along and across the shore. Phases of dune activity associated with variation in the intensity and duration of metocean processes will continue to contribute to development of the dune ridge through the formation and destruction of foredunes, blowout activity and the migration of nested parabolic sand dunes. With the exception of the coast between the Gascoyne River mouth and Currandura Well, many of the barriers overly coastal limestone and sandstone terrain - an indication that they may be sediment deficient and have been subject to retreat during the late Holocene. At a similar geological timescale, the reef and headlands provide topographic control for the formation of sedimentary accumulation landforms, such as sand banks, sills, salients, cuspate forelands and tombolos.

Medium time scales are relevant to landform changes occurring over decades and centuries, including changes to dune barriers as well as the intertidal and sub-tidal terrace formations skirting the shore (Brown 1988; Leeden 2003). In this context, dune formation and migration on the barrier is ultimately dependent on sediment supply from offshore and alongshore, and is associated with long-term variability in metocean processes. At present the alongshore component of littoral sediment transport (nett northerly), superimposed by circulation patterns developed through reef and lagoon structure (Hearn *et al.* 1986; Sanderson 2000; D'Adamo & Simpson 2001) is critical to coastal stability and future evolution of accretionary landforms. The ramifications of this are that the future medium-term stability of the coast will potentially be affected by rates of onshore sediment supply, any updrift interference with the coastal sediment transport, or modification to the reef or headland controls, as well as by natural variability and change to metocean processes. Changes in sediment supply and dominance of the southerly component of governing metocean processes are contributing to the northwards migration of some of the sedimentary accumulation landforms on the coast (Sanderson 2000), including spits along the Shark Bay coast and cuspate forelands of the Ningaloo coast. In some places the intertidal accretionary forms, spits and bars, have closed bay mouths and impounded small coastal lagoons.

Local changes are also active over medium time scales as well as at sub-decadal scales, as any destabilisation and landward movement of the dunes results in a loss of sand from the adjacent shore and exposure of rocky terrain, including pavement, beachrock ramps and platforms. In areas where dunes have formed, changes in beach width largely correspond with dune and blowout activity; examples occur along Miaboolya Beach, parts of the Ningaloo coast and in the vicinity of Gnaraloo. Sandsheets have continued to form and rapidly migrate north (northeast to northwest dependent on the local wind climate and topography), as has occurred at Gnaraloo. Other localised responses of accretionary landforms to metocean changes include gradual modification of spits and bars on subtidal and intertidal terraces (including Babbage Island spit), bar opening and closing at the mouths of intermittent streams, and localised erosion and recovery of beaches and foredunes in the vicinity of headlands and rock outcrops along the shore.

At sub-decadal time scales modern metocean processes interact with the inherited geologic framework. The alongshore variation in coastal alignment, beach erosion and deposition, foredune formation and dune development occurs as a result of interaction of the geologic framework and metocean processes with reaches of coast most susceptible to environmental change. This commonly occurs in close proximity to shoreline salients and extensive rock outcrops. Localised estimation of shoreline change is necessary and should be linked to geophysical determination of the distribution and elevation of the underlying rocky terrain supporting the barrier.

On an event scale, the response of sub tidal terraces, beaches, foredunes, primary dunes and river deltas to storms is localised, with the sediment transport influenced by the broad scale metocean processes along with the local influences of inner shelf structure, coastal aspect, reef structure, geologic framework, presence of subtidal terraces or tidal flats, groundwater flows, deltaic systems and sediment availability (Section 4.3). The rate of recovery during lower energy periods varies along the Gascoyne coast and is markedly influenced by the underlying rock structure.

4.5.3. Shoreline Movement

Naturally occurring movement of the shoreline has implications for proposed and existing coastal land use under the State Coastal Planning Policy SPP No. 2.6 (WAPC 2003). Shoreline change is typically described in terms of cross-shore and alongshore sediment movement (van Rijn 1998). The separation is fundamentally based upon geomorphic time scales, where cross-shore transport most commonly occurs under high frequency fluctuations associated with storms and water level variations; and nett alongshore transport is considered to represent slower changes, which may be evolutionary in nature. For example, from an analysis of 16 years of monthly data from Scarborough Beach, Clarke and Eliot (1983, 1987) attribute less than 5% of nett annual sediment movement to alongshore transport, despite being the major mechanism for long-term change. Although the distinction between cross-shore and alongshore transport is convenient, it is not altogether accurate. Significant alongshore transport also may occur pulsationally and over short times frames, particularly where the inshore bathymetry is complex and there is periodic supply of sediments along and offshore associated with river flooding and through reef gaps and from inshore banks and bars, as it is on the Gascoyne coast. Similarly, cross-shore transport may not always have a nett zero change over years or even decades.

Cross-shore processes are evidenced by the presence of shore parallel bar and bedform features in the nearshore waters, scarped foredunes or frontal dunes, mobile frontal dunes where sediment is actively moving inland from the shore, storm bars and washover features. The effect of alongshore transport is apparent through the geological structure of the barrier and its landform patterns, the beach profile configuration in sheltered environments (Nordstrom 1992), spits, cheniers and strandplains. The analysis applied to the Gascoyne coast examined changes to beach, coastal dune, salient, spits and alluvial components discernable from available aerial photography as well as ground reconnaissance. It provided an indication of the areas susceptible to change as well as the relative stability of landforms within each focal sediment cell. For example, in some places the barrier is susceptible to becoming unstable and subsequently eroding, particularly where vegetation has been removed or the frontal dunes, those closest to the shore, have been activated by metocean processes.

More detailed analysis of coastal change was completed for fifteen Areas of Planning Interest (Section 6). Vertical aerial photographs were examined for the earliest available record (1957-1964) to the most recent (1999-2010), with further years in between for certain sites. Although this approach does not quantify shoreline, spit and dune movement, comparison of the photographs indicates change in the shoreline position is localised to areas in the vicinity of river deltas and streams, between rock outcrops and on perched beaches, areas with spit and storm bar migration within Shark Bay or corresponding to migration of salients and cuspate forelands. In places, dunes migrate northwest; however, the photographic record is not sufficiently frequent to pinpoint the number of phases of accelerated migration and when each occurred.

In the context of long-term planning, coastal stability evaluation requires consideration of potential changes over a range of time scales, from the short-term acute storm erosion, longer-term patterns of coastal evolution and impacts of projected climate change (Allan *et al*. 2003). These factors are considered within the State Coastal Planning Policy SPP No. 2.6 (WAPC 2003) through horizontal setback allowances for acute change, chronic change and sea level rise (S1, S2 and S3 respectively). The allowance for chronic change S2 is calculated as 100 times the assessed present longer-term rate of erosion.

Vegetation lines determined from vertical aerial photography are a commonly applied shoreline proxy nominated in SPP No. 2.6 as a measure for change on sandy shores that are not influenced by tropical cyclones. This measure may be limited along sections of the Gascoyne coast, including areas with mangroves, rock, sub-tidal terraces, mudflats and outwash plains. For these shore types significant vertical variation of the nearshore seabed may occur without becoming apparent in the position of the adjacent vegetation or when assessed directly from above (Boak & Turner 2005). Consequently, vegetation line changes provide a poor proxy for coastal volumetric change, particularly on low lying and rocky coasts. In this case, oblique aerial photography collected as part of WACoast (Gozzard 2012) has been used in conjunction with vertical aerial photography to qualitatively describe historical change. The S2 component under SPP No. 2.6 *Schedule One* for these coasts may be evaluated through consideration of landform changes and the inter-relationships between landforms to develop an estimate of the overall sediment budget (Whitehouse *et al.* 2009a; Damara WA 2011).

Overall the historic record indicates the Gascoyne shoreline is variable temporally and spatially, with areas of sediment accumulation and other areas with a retreating barrier. The area with greatest variability is the active Gascoyne River delta; on the subtidal terraces, tidal flats and outwash plains; and localised dune breakouts backed to landward by ephemeral creeks. Variability also occurs at cuspate forelands and salients, at recurved spits and storm bars, and on perched beaches.

4.6. PROJECTED FUTURE CHANGE

Projected coastal change over a planning time frame should account for the cumulative effect of gradual progressive change, the potential influence of extreme conditions and the possible effect of shifts in the environmental conditions brought about by climate variation (including climate change) and human intervention.

As the predominant geomorphic character of the Gascoyne coast can be described as inherited (see Section 4.5), implications of projected climate change and variability need to be considered relative to the environmental conditions responsible for the coastal configuration. Land-shaping conditions vary significantly between individual landform elements, but along the Gascoyne coast, simple distinctions should be made between elements shaped by (i) modern or historic environmental conditions; and (ii) by prevailing or extreme conditions.

The combination of projecting modern trends, allowance for acute event response and estimation of change to the mean conditions is appropriate for landform elements shaped by prevailing modern processes. SPP No. 2.6 suggests a methodology for the calculation of setback allowance on a sandy beach that incorporates these principles.

The modern record of change may not reflect likely future change for those elements apparently formed by historic conditions. Sensitivity to climate change ‘tipping points’ should be established, which may modify the observed modern trend, enable acute response to occur where it has not been observed in the modern record, or may produce large changes in the incidence of land-shaping events.

For those elements apparently shaped by extreme conditions, additional focus is required to define the likelihood of such extreme environmental conditions, and the potential change due to climate shifts. This approach is commonly applied to risk assessment of dune breaching (Dekker *et al*. 2005; Larson *et al*. 2009).

In the context of the present landform vulnerability assessment, landform instability is strongly tied to the era in which the landform was shaped. Those features which experience high instability are typically responsive to modern processes. Landform susceptibility is indicative of the type of event which significant for landform shaping. Low susceptibility landforms are usually insensitive to prevailing conditions, and may only be affected by extreme events.

5. Land System Stability and Susceptibility to Change

The Gascoyne coast comprises seven primary, twenty four secondary compartments and forty eight tertiary compartments (Figure 1-2 to Figure 1-5; Table 2-1). In its northern reaches the Study Area partly extends into an eighth primary compartment, the Eastern Gulf which includes the Yannarie salt flats. The vulnerability of the seven complete primary compartments, including the Zuytdorp, Freycinet, L'Haridon, Gascoyne, MacLeod, Ningaloo and Western Gulfcompartments (Figure 1-2), has previously been considered by Eliot *et al.* (2011) for strategic planning. They are not considered at this scale further in this report.

Secondary compartments are considered at a land system scale appropriate to strategic planning. Land systems for the twenty four secondary compartments have been identified, mapped (Appendix C) and their geology, geomorphology and landforms described (Appendix D). Tertiary compartments were not considered in this study, given its focus on broad strategic planning and local area planning.

Sediment cells of the Gascoyne coast are considered in detail at a landform scale appropriate to local area planning for fifteen Areas of Planning Interest (Figure 1-2 to Figure 1-5; Table 2-1; Section 6). The Areas of Planning Interest include fifteen primary sediment cells and five secondary sediment cells. The landforms for each sediment cell have been identified, mapped and described at a finer spatial scale than that used to describe the secondary compartments. The descriptions are presented for groups of adjacent cells (Appendix G).

The groups of cells are those in the vicinity of:

- Nanga (Appendix G1; Figure G-1; Figure G-2; Table G-1);
- Denham and Little Lagoon (Appendix G2; Figure G-3; Figure G-4; Table G-5);
- Monkey Mia (Appendix G3; Figure G-5; Figure G-6; Table G-9);
- Carnarvon and Miaboolya Beach (Appendix G4; Figure G-7; Figure G-8; Table G-13);
- Quobba-Blowholes and Quobba Station (Appendix G5; Figure G-9; Figure G-10; Table G-17);
- Red Bluff, Three Mile Camp, Gnaraloo Station and Gnaraloo Bay (Appendix G6; Figure G-11; Figure G-12; Table G-21);
- Coral Bay (Appendix G7; Figure G-13; Figure G-14; Table G-25);
- Vlamingh Head (Appendix G8; Figure G-15; Figure G-16; Table G-29); and
- Exmouth (Appendix G9; Figure G-17; Figure G-18; Table G-33).

5.1. LAND SYSTEM SUSCEPTIBILIY & INSTABILITY

The major natural structural features of the secondary compartments as well as their present and potential future landform stability are discussed separately prior to addressing vulnerability.

5.1.1. Susceptibility

The major natural structural features of the secondary compartments were described (Appendix E) and ranked (Table 5-1) according to their likely susceptibility to change.

Seventeen of the 24 (71%) secondary compartments have a low susceptibility. Five secondary compartments (21%) are moderately susceptible and two (8%) are highly susceptible. The implications of the groupings into low, moderate and high categories are summarised for each compartment in Appendix F.

Secondary compartments have low susceptibility where the coast is protected by a nearly continuous offshore reef or a wide shelf; there is a wide sub-tidal terrace or bank; rock outcrops with some cliffs and bluffs outcrop along the shore; the coast is sheltered from metocean forcing; beaches are perched on an intertidal rock surface; and/or the dune barrier is likely to be perched on a rock surface above the highest astronomic tide. The areas with low susceptibility are the:

- Zuytdorp cliffs with narrow a continental shelf, including two compartments between Nunginjay Spring Coast North and Cape Inscription;
- Six compartments within Shark Bay between Cape Bellefin and Nilemah Coast East with wide sub-tidal terraces underpinned by the geologic framework;
- Wooramel Bank with a wide sub-tidal terrace, inherited deltaic features and tidal flats, including two compartments from Nilemah Coast East to Grey Point;
- Five compartments along Ningaloo coast from Cape Cuvier to North West Cape with the exception of the highly susceptible Point Cloates to Winderabandi Point. The five have shallow coral reefs, inshore lagoons, bluffs, perched dunes and arcuate coasts; and
- Western Exmouth Gulf, including two compartments extending from Northwest Cape to Giralia that are partially sheltered from swell and have sub-tidal terraces, receded barriers, rocky coasts and some inherited deltaic features in the south.

Secondary compartments considered moderately susceptible to change are exposed to metocean forcing; have unconsolidated landforms; part of active river deltas; and lack bedrock support or offshore reefs are not common in the Study Area. The moderately susceptible secondary compartments are:

- Murchison River to Nunginjay Spring Coast North with a westerly aspect, deep intermittent reef and a source of sediment from the Murchison River;
- Cape Inscription to Cape Bellefin on eastern Dirk Hartog Island with unconsolidated inshore sediments, a northerly aspect and no barrier;
- South Bejaling Hill to Point Quobba with shallow intermittent reef, high exposure, beach rock and dunes above high tide level;
- Point Quobba to Cape Cuvier with extensive platforms and cliffs on an exposed coast with deep inshore bathymetry; and
- Giralia to Locker Point with inherited deltaic features and wide tidal flats.

The two tracts of coast highly susceptible to change in the natural structure are Grey Point to South Bejaling Hill which are part of the active Gascoyne River delta; and Point Cloates to Winderabandi Point which has a westerly aspect, cuspate forelands and a sandy shoreface.

A summary of the three levels of susceptibility across primary and secondary compartments, and the sediment cells encompassing the Areas of Planning Interest is shown in Table 5-2. This table demonstrates the adjustment of the susceptibility ranking with the scale of investigation because the proportion of coast comprising particular natural structural features, land systems and landforms changes with scale. It also highlights the need for very detailed examination of landforms and processes at local planning scales.

Table 5-1: Susceptibility Rankings for Each Secondary Compartment

Secondary Compartment	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking
Giralia to Locker Point	1	4	2	4	11	M
Learmonth to Giralia	1	1	2	3	7	L
North West Cape to Learmonth	1	1	3	2	7	L
Winderabandi Point to North West Cape	2	1	2	3	8	L
Point Cloates to Winderabandi Point	2	5	5	4	16	H
Point Maud to Point Cloates	2	3	3	1	9	L
Alison Point to Point Maud	1	1	3	1	6	L
Gnaraloo Bay to Alison Point	2	2	3	2	9	L
Cape Cuvier to Gnaraloo Bay	3	2	3	1	9	L
Point Quobba to Cape Cuvier	4	3	5	1	13	M
South Bejaling Hill to Point Quobba	3	4	5	1	13	M
Grey Point to South Bejaling Hill	2	5	3	5	15	H
Wooramel coast to Grey Point	1	1	2	4	8	L
Nilemah coast E to Wooramel coast	1	1	3	4	9	L
Petit Point to Nilemah coast E	1	1	2	2	6	L
Monkey Mia to Petit Point	1	1	3	3	8	L
Cape Peron North to Monkey Mia	2	1	3	3	9	L
Goulet Bluff to Cape Peron North	2	1	3	2	8	L
Giraud Point to Goulet Bluff	2	1	3	3	9	L
Cape Bellefin to Giraud Point	2	1	2	3	8	L
Cape Inscription to Cape Bellefin	5	1	3	2	11	M
Steep Point to Cape Inscription	4	1	1	1	7	L
Nunginjay Spring Coast North to Steep Point	4	1	1	1	7	L
Murchison River to Nunginjay Spring Coast North	4	2	5	1	12	M

The seven complete primary compartments have been attributed a moderate or high susceptibility ranking based on the land systems present. The eighth compartment (Eastern Gulf) has a high susceptibility. The highly susceptible primary compartments are comprised of low-lying land systems with gulfs and are subject sea level ranging.

Sediment cells in the Areas of Planning Interest are addressed in Section 6. Twenty cells were considered with six ranked as low susceptibility, 11 as moderate susceptibility and three as high susceptibility. Many of the cells have a higher susceptibility ranking when considered at a finer spatial scale than secondary compartments because the more susceptible natural structural features, such as cuspate forelands comprise a higher proportion of the coast of interest.

Table 5-2: Susceptibility for Compartments and Cells
Primary compartment rankings are from the approach in Figure 5-2 (Eliot *et al.* 2011)
Only the sediment cells relevant for the Areas of Planning Interest were assessed
Susceptibility and Instability Rankings should not be used Independently

Primary Compartment	Rank	Secondary Compartment	Rank	Primary or Secondary Cell	Rank
EASTERN GULF: Giralia to Locker Point	H	Giralia to Locker Point	M		
WESTERN GULF: North West Cape to Giralia	H	Learmonth to Giralia	L		
		North West Cape to Learmonth	L	20. Exmouth North to Qualing Pool	L
				19. Bundegi to Exmouth North	L
NINGALOO: Alison Point to North West Cape	M	Winderabandi Point to North West Cape	L	18. Vlamingh Head to East Vlamingh	L
				17. Babjarrimannos to Vlamingh Head	L
		Point Cloates to Winderabandi Point	H		
		Point Maud to Point Cloates	L		
		Alison Point to Point Maud	L	16. Purdy Point to Point Maud	M
				15. Point Anderson to Purdy Point	M
MACLEOD: Point Quobba to Alison Point	M	Gnaraloo Bay to Alison Point	L	14. Gnaraloo Bay South to Gnaraloo Bay North	M
		Cape Cuvier to Gnaraloo Bay	L	13. Gnaraloo North to Gnaraloo Bay South	M
				12. Gnaraloo South to Gnaraloo North	M
				11. Red Bluff to Gnaraloo South	L
		Point Quobba to Cape Cuvier	M	10. Quobba Station S to Quobba Station N	M
GASCOYNE: Grey Point to Point Quobba	M	South Bejaling Hill to Point Quobba	M	9. Fitzroy Reefs to Point Quobba	M
		Grey Point to South Bejaling Hill	H	8. Gascoyne River North to Miaboolya Beach	H
				7. Gascoyne River South to Gascoyne River North	H
				6. Massey Bay to Gascoyne River South	H
L'HARIDON: Cape Peron North to Grey Point	H	Wooramel coast to Grey Point	L		
		Nilemah coast E to Wooramel coast	L		
		Petit Point to Nilemah coast E	L		
		Monkey Mia to Petit Point	L	5. Monkey Mia to Eastern Bluff	M
		Cape Peron North to Monkey Mia	L	4. Red Cliff Bay to Monkey Mia	M
FREYCINET: Cape Inscription to Cape Peron North	M	Goulet Bluff to Cape Peron North	L	3. Lagoon Point to Middle Bluff	M
				2. Denham South to Lagoon Point	L
		Giraud Point to Goulet Bluff	L	1. Nanga Bay to Goulet Bluff	M
		Cape Bellefin to Giraud Point	L		
		Cape Inscription to Cape Bellefin	M		
ZUYTDORP: Murchison River to Cape Inscription	M	Steep Point to Cape Inscription	L		
		Nunginjay Spring C. N to Steep Point	L		
		Murchison River to Nunginjay Spring C. N	M		

5.1.2. Instability

The present instability of landform features in the secondary compartments was described (Appendix E) and the compartments ranked according to their likely instability (Table 5-3). Difference between the rankings for susceptibility and instability assigned to the same compartment are notable and highlight the significance of long-term versus short-term change. The majority of the secondary compartments, 17 of the 24 (71%) have a low instability, which is to say they are stable compared to other compartments in the region. Five secondary compartments (21%) are moderately unstable and two (8%) are highly unstable. The implications of the groupings into low, moderate and high categories are summarised for each compartment in Appendix F.

Secondary compartments are relatively stable and display low instability where the coast has a limited amount of sediment stored inshore with sheltering by inshore reefs and/or rocky pavement; sandy beachface is either not present, perched on rock or has a sheltered profile; the frontal dune complex is relatively intact or perched on rock above highest astronomic tide; the barrier dunes are well vegetated; and/or they have vegetated tidal flats with few tidal creeks or a continuously lithified chenier ridge. The areas with low landform instability are the:

- Zuytdorp cliffs without a barrier or beach. This includes two compartments extending between Nunginjay Spring coast N and Cape Inscription;
- Shark Bay compartments, including six between Cape Bellefin and Nilemah Coast East. The compartments have sheltered sandy beaches perched on inshore rock platforms and discontinuous or partly scarped foredunes.
- Southern Wooramel Bank, from Nilemah Coast East to Wooramel Coast ,with inshore rock pavement, sheltered beachfaces and moderately stable tidal flats;
- Ningaloo coast from Point Quobba to North West Cape with the exception of the moderately-unstable Point Cloates to Winderabandi Point, includes six secondary compartments. It has sheltered beachfaces perched on inshore rock and is in the lee of reef, has less than 25% active dunes and some frontal dune scarping; and
- Western Exmouth Gulf has two secondary compartments between Northwest Cape and Giralia with sheltered beachfaces perched on inshore rock and moderately stable foredunes.

The secondary compartments with moderately unstable landforms are not common in the Study Area. Combinations of some of the following factors indicate present levels of landform instability: the inshore seabed containing more bare sand; beaches commonly subject to higher wave conditions or river activity; there are fewer foredunes and the frontal dune may be cliffed; vegetation cover is low and mobile dunes are present on the barrier; and tidal flats have less vegetation and more tidal creeks. The moderately unstable secondary compartments are:

- Cape Inscription to Cape Bellefin on eastern Dirk Hartog Island with bare sand surfaces in the inshore;
- Wooramel Coast to Grey Point with bare sand in the inshore and tidal flats with many tidal creeks and limited vegetation landward of the area affected by surge;
- Grey Point to South Bejaling Hill with contemporary sediment supplied by the Gascoyne River and reworking of these and older sediments across the inshore, beachface, foredunes and frontal dunes;
- Point Cloates to Winderabandi Point, which has bare sand surfaces inshore of reef, more exposed beaches and active foredunes, frontal dunes and mobile dunes; and
- Giralia to Locker Point, where there are bare tidal flats with many tidal creeks and limited vegetation.

Two tracts of coast with highly unstable landforms are the two compartments immediately north of active river systems, the Murchison and the Gascoyne Rivers. The compartments are: Murchison River to Nunginjay Spring Coast North with an exposed perched beach on shallow pavement, scarped frontal dune and a source of sediment from the Murchison River to the south; and South Bejaling Hill to Point Quobba with less than 25% reef with a source of sediment from the Gascoyne River to the south, exposed beaches, low frontal dune vegetation cover and some mobile dunes.

Table 5-3: Instability Rankings for Each Secondary Compartment

Secondary Compartment	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune Complex or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking
Giralia to Locker Point	3	2	3	4	12	M
Learmonth to Giralia	1	2	3	3	9	L
North West Cape to Learmonth	1	2	3	2	8	L
Winderabandi Point to North West Cape	1	2	3	2	8	L
Point Cloates to Winderabandi Point	4	3	3	3	13	M
Point Maud to Point Cloates	2	2	3	2	9	L
Alison Point to Point Maud	1	2	2	2	7	L
Gnaraloo Bay to Alison Point	1	3	2	2	8	L
Cape Cuvier to Gnaraloo Bay	2	2	3	2	9	L
Point Quobba to Cape Cuvier	1	2	3	2	8	L
South Bejaling Hill to Point Quobba	4	4	4	3	15	H
Grey Point to South Bejaling Hill	4	3	3	3	13	M
Wooramel coast to Grey Point	4	2	3	4	13	M
Nilemah coast E to Wooramel coast	1	2	2	3	8	L
Petit Point to Nilemah coast E	1	2	3	3	9	L
Monkey Mia to Petit Point	2	2	2	2	8	L
Cape Peron North to Monkey Mia	2	2	2	2	8	L
Goulet Bluff to Cape Peron North	3	2	2	2	9	L
Giraud Point to Goulet Bluff	3	2	1	1	7	L
Cape Bellefin to Giraud Point	3	1	2	1	7	L
Cape Inscription to Cape Bellefin	4	2	2	2	10	M
Steep Point to Cape Inscription	3	1	1	1	6	L
Nunginjay Spring Coast North to Steep Point	3	1	1	1	6	L
Murchison River to Nunginjay Spring Coast North	2	5	5	3	15	H

A summary of the three levels of instability across primary and secondary compartments, and the focal sediment cells is shown in Table 5-4. This table again demonstrates the adjustment of landform rankings, in this case instability rankings, with the scale of investigation because the proportion of coast comprising particular unstable landforms changes with scale.

The seven complete primary compartments have been attributed a moderate instability ranking based on the landforms and land systems present. The eighth compartment (Eastern Gulf, between Giralia and Locker Point) has a high instability.

Sediment cells in the Areas of Planning Interest are described in Section 6. Twenty cells were examined with nine ranked as low instability, eight as moderate instability and three as high instability. Many of the cells have a higher instability ranking when considered at a finer spatial scale than secondary compartments because the more unstable landforms, such as active dunes and scarped foredunes, represent a higher proportion of the coast of interest.

Table 5-4: Instability for Compartments and Cells
Primary compartment rankings are from the approach in Figure 5-2 (Eliot *et al.* 2011)
Only the sediment cells relevant for the Areas of Planning Interest were assessed
Susceptibility and Instability Rankings should not be used Independently

Primary Compartment	Rank	Secondary Compartment	Rank	Primary or Secondary Cell	Rank
EASTERN GULF: Giralia to Locker Point	H	Giralia to Locker Point	M		
WESTERN GULF: North West Cape to Giralia	M	Learmonth to Giralia	L		
		North West Cape to Learmonth	L	20. Exmouth North to Qualing Pool	L
				19. Bundegi to Exmouth North	M
NINGALOO: Alison Point to North West Cape	M	Winderabandi Point to North West Cape	L	18. Vlamingh Head to East Vlamingh	L
				17. Babjarrimannos to Vlamingh Head	L
		Point Cloates to Winderabandi Point	M		
		Point Maud to Point Cloates	L		
		Alison Point to Point Maud	L	16. Purdy Point to Point Maud	L
				15. Point Anderson to Purdy Point	M
MACLEOD: Point Quobba to Alison Point	M	Gnaraloo Bay to Alison Point	L	14. Gnaraloo Bay South to Gnaraloo Bay North	M
		Cape Cuvier to Gnaraloo Bay	L	13. Gnaraloo North to Gnaraloo Bay South	L
				12. Gnaraloo South to Gnaraloo North	M
				11. Red Bluff to Gnaraloo South	M
		Point Quobba to Cape Cuvier	L	10. Quobba Station S to Quobba Station N	M
GASCOYNE: Grey Point to Point Quobba	M	South Bejaling Hill to Point Quobba	H	9. Fitzroy Reefs to Point Quobba	M
		Grey Point to South Bejaling Hill	M	8. Gascoyne River North to Miaboolya Beach	H
				7. Gascoyne River South to Gascoyne River North	H
				6. Massey Bay to Gascoyne River South	H
L'HARIDON: Cape Peron North to Grey Point	M	Wooramel coast to Grey Point	M		
		Nilemah coast E to Wooramel coast	L		
		Petit Point to Nilemah coast E	L		
		Monkey Mia to Petit Point	L	5. Monkey Mia to Eastern Bluff	L
		Cape Peron North to Monkey Mia	L	4. Red Cliff Bay to Monkey Mia	L
FREYCINET: Cape Inscription to Cape Peron North	M	Goulet Bluff to Cape Peron North	L	3. Lagoon Point to Middle Bluff	M
				2. Denham South to Lagoon Point	L
		Giraud Point to Goulet Bluff	L	1. Nanga Bay to Goulet Bluff	L
		Cape Bellefin to Giraud Point	L		
		Cape Inscription to Cape Bellefin	M		
ZUYTDORP: Murchison River to Cape Inscription	M	Steep Point to Cape Inscription	L		
		Nunginjay Spring C. N to Steep Point	L		
		Murchison River to Nunginjay Spring C. N	H		

5.2. LAND SYSTEM VULNERABILITY

The vulnerability of the secondary compartments was estimated by combining the overall rankings for susceptibility and instability to identify the likelihood of geomorphic change, grouped into five categories (Table 5-5; Figure 5-1; Appendix C). Descriptions of the main natural structural features and landform instability for each compartment are included in Appendix E. The majority of the secondary compartments, 16 of the 24 (67%) have a low vulnerability. Two secondary compartments (8%) have low-to-moderate vulnerability, two (8%) have moderate vulnerability, four (17%) have a moderate-to-high vulnerability and none had a high vulnerability. The implications of the groupings into low, low-to-moderate,

moderate and moderate-to-high categories are summarised for each compartment in Appendix F.

The secondary compartments with low vulnerability are those with less susceptible natural structural features and low landform instability, as described in Section 5.1 above. The areas with low vulnerability, where coastal risk is unlikely to be a constraint to coastal management at a secondary compartment scale, are the:

- Zuytdorp cliffs, including the two compartments from Nunginjay Spring Coast North to Cape Inscription;
- Shark Bay, including the six compartments from Cape Bellefin to Nilemah Coast East;
- Southern Wooramel Bank , extending from Nilemah Coast East to Wooramel Coast;
- Ningaloo coast, including the five compartments from Cape Cuvier to North West Cape but with the exception of Point Cloates to Winderabandi Point which has a moderate-to-high vulnerability; and
- Western Exmouth Gulf, with two compartments between Northwest Cape and Giralia.

The secondary compartments with low-to-moderate vulnerability are those with less susceptible natural structural features or low landform instability. They are areas where coastal risk is likely to present a low constraint to coastal management at a secondary compartment scale. The two compartments are Wooramel coast to Grey Point with moderate instability associated with active inshore sediments and tidal flats; and the exposed Point Quobba to Cape Cuvier with moderate susceptibility associated with deep inshore bathymetry and extensive platforms and cliffs.

Secondary compartments of the Gascoyne coast with moderate vulnerability are those with moderately susceptible natural structural features and moderate landform instability. These are areas where coastal risk may present a moderate constraint to coastal management at a secondary compartment scale. The two compartments are Cape Inscription to Cape Bellefin with unconsolidated sediments active in the inshore, a northerly aspect and no barrier; and Giralia to Locker Point with wide tidal flats with inherited deltaic features, many tidal creeks and limited vegetation landward of the area affected by surge.

The secondary compartments with moderate-to-high vulnerability are those with highly susceptible natural structural features or high landform instability. These are areas where coastal risk is likely to be a significant constraint to coastal management at a secondary compartment scale. The two compartments highly susceptible to change are associated with mobile structures on the active Gascoyne River delta between Grey Point and South Bejaling Hill and the cuspate forelands from Point Cloates to Winderabandi Point. The two compartments with highly unstable landforms are immediately north of active river systems, they extend from the Murchison River to Nunginjay Spring Coast North immediately north of the Murchison River and from South Bejaling Hill near the Gascoyne River to Point Quobba.

A summary of the five levels of vulnerability across primary and secondary compartments, and the focal sediment cells is shown in Table 5-6. This table again indicates the adjustment of the vulnerability rankings with the scale of investigation because the proportion of coast comprising susceptible natural structural features and/or particular unstable landforms changes with scale.

Table 5-5: Susceptibility, Instability and Vulnerability for Each Secondary Compartment

Secondary Compartment	Susceptibility Rank	Instability Rank	Vulnerability Rank
Giralia to Locker Point	M	M	M
Learmonth to Giralia	L	L	L
North West Cape to Learmonth	L	L	L
Winderabandi Point to North West Cape	L	L	L
Point Cloates to Winderabandi Point	H	M	M-H
Point Maud to Point Cloates	L	L	L
Alison Point to Point Maud	L	L	L
Gnaraloo Bay to Alison Point	L	L	L
Cape Cuvier to Gnaraloo Bay	L	L	L
Point Quobba to Cape Cuvier	M	L	L-M
South Bejaling Hill to Point Quobba	M	H	M-H
Grey Point to South Bejaling Hill	H	M	M-H
Wooramel coast to Grey Point	L	M	L-M
Nilemah coast E to Wooramel coast	L	L	L
Petit Point to Nilemah coast E	L	L	L
Monkey Mia to Petit Point	L	L	L
Cape Peron North to Monkey Mia	L	L	L
Goulet Bluff to Cape Peron North	L	L	L
Giraud Point to Goulet Bluff	L	L	L
Cape Bellefin to Giraud Point	L	L	L
Cape Inscription to Cape Bellefin	M	M	M
Steep Point to Cape Inscription	L	L	L
Nunginjay Spring coast N to Steep Point	L	L	L
Murchison River to Nunginjay Spring coast N	M	H	M-H

Key	Vulnerability of environmental change	Implications for coastal management (see Table 2-11 for further description)
(green)	Low	Coastal risk is unlikely to be a constraint to coastal management
(light green)	Low -to-moderate	Coastal risk may present a low constraint to coastal management
(yellow)	Moderate	Coastal risk may present a moderate constraint to coastal management
(peach)	Moderate-to-high	Coastal risk is likely to be a significant constraint to coastal management
(red)	High	Coastal risk is a highly significant constraint to coastal management

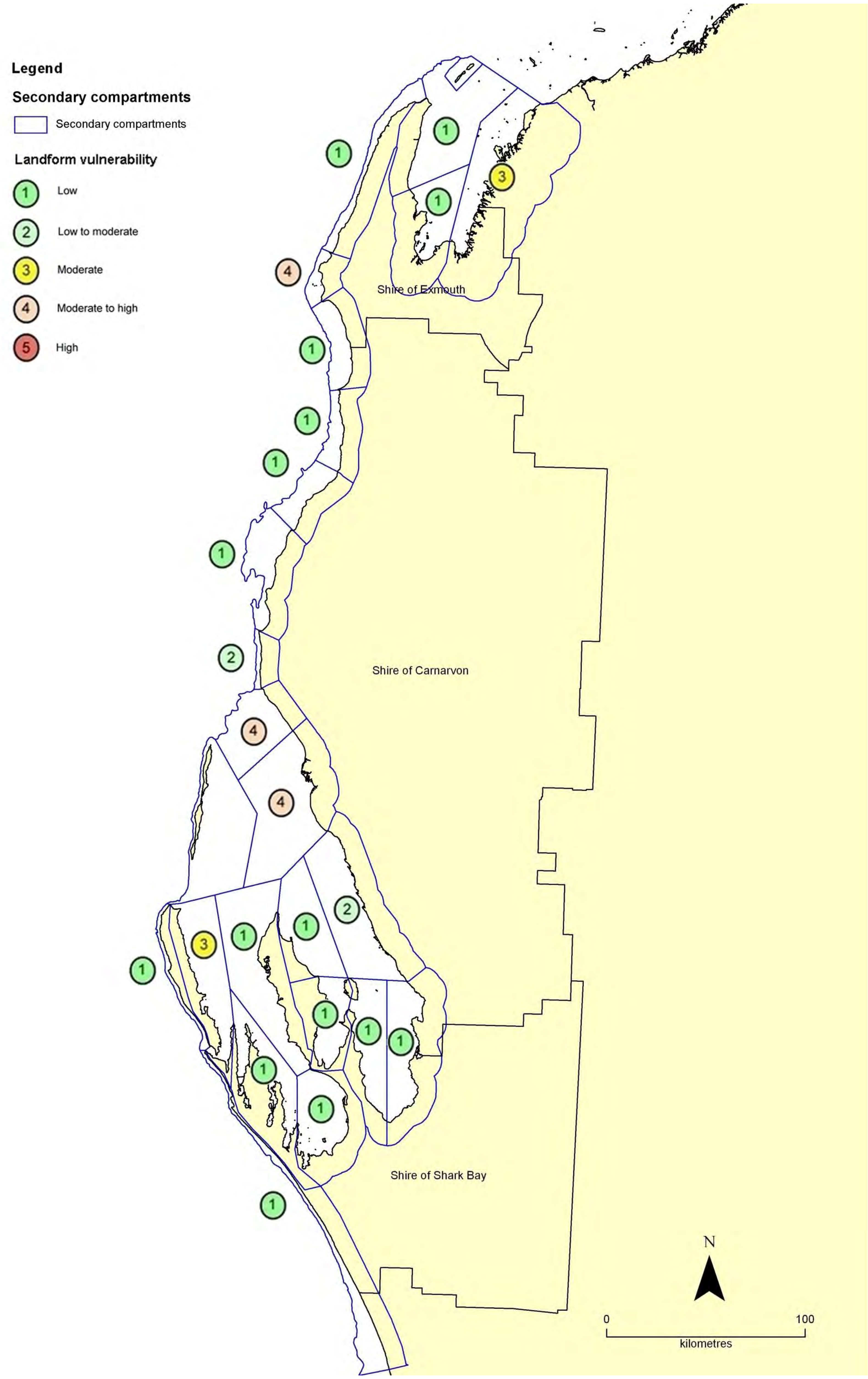


Figure 5-1: Vulnerability Rankings of Secondary Compartments of the Gascoyne Coast
Compartment labels contained in Figure 1-3 to Figure 1-5

Table 5-6: Vulnerability for Compartments and Cells
Primary compartment rankings are from the approach in Figure 5-2 (Eliot *et al.* 2011)
Only the sediment cells relevant for the Areas of Planning Interest were assessed

Primary Compartment	Rank	Secondary Compartment	Rank	Primary or Secondary Cell	Rank
EASTERN GULF: Giralia to Locker Point	H	Giralia to Locker Point	M		
WESTERN GULF: North West Cape to Giralia	M-H	Learmonth to Giralia	L		
		North West Cape to Learmonth	L	20. Exmouth North to Qualing Pool	L
				19. Bundegi to Exmouth North	L-M
NINGALOO: Alison Point to North West Cape	M	Winderabandi Point to North West Cape	L	18. Vlamingh Head to East Vlamingh	L
				17. Babjarrimannos to Vlamingh Head	L
		Point Cloates to Winderabandi Point	M-H		
		Point Maud to Point Cloates	L		
		Alison Point to Point Maud	L	16. Purdy Point to Point Maud	L-M
				15. Point Anderson to Purdy Point	M
MACLEOD: Point Quobba to Alison Point	M	Gnaraloo Bay to Alison Point	L	14. Gnaraloo Bay South to Gnaraloo Bay North	M
		Cape Cuvier to Gnaraloo Bay	L	13. Gnaraloo North to Gnaraloo Bay South	L-M
				12. Gnaraloo South to Gnaraloo North	M
				11. Red Bluff to Gnaraloo South	L-M
		Point Quobba to Cape Cuvier	L-M	10. Quobba Station S to Quobba Station N	M
GASCOYNE: Grey Point to Point Quobba	M	South Bejaling Hill to Point Quobba	M-H	9. Fitzroy Reefs to Point Quobba	M
		Grey Point to South Bejaling Hill	M-H	8. Gascoyne River North to Miaboolya Beach	H
				7. Gascoyne River South to Gascoyne River North	H
				6. Massey Bay to Gascoyne River South	H
L'HARIDON: Cape Peron North to Grey Point	M-H	Wooramel coast to Grey Point	L-M		
		Nilemah coast E to Wooramel coast	L		
		Petit Point to Nilemah coast E	L		
		Monkey Mia to Petit Point	L	5. Monkey Mia to Eastern Bluff	L-M
		Cape Peron North to Monkey Mia	L	4. Red Cliff Bay to Monkey Mia	L-M
FREYCINET: Cape Inscription to Cape Peron North	M	Goulet Bluff to Cape Peron North	L	3. Lagoon Point to Middle Bluff	M
				2. Denham South to Lagoon Point	L
		Giraud Point to Goulet Bluff	L	1. Nanga Bay to Goulet Bluff	L-M
		Cape Bellefin to Giraud Point	L		
		Cape Inscription to Cape Bellefin	M		
ZUYTDORP: Murchison River to Cape Inscription	M	Steep Point to Cape Inscription	L		
		Nunginjay Spring C. N to Steep Point	L		
		Murchison River to Nunginjay Spring C. N	M-H		

The seven complete primary compartments have been attributed a moderate or moderate-to-high vulnerability ranking based on the natural structural features and landform stability present (Figure 5-2). The eighth compartment (Eastern Gulf between Giralia and Locker point) has a high vulnerability.

The focal sediment cells are addressed in Section 6. Twenty cells were considered with four ranked as low vulnerability, seven as low-to-moderate, six as moderate, none as moderate-to-high and three as high vulnerability. Many of the cells have a higher vulnerability ranking when considered at a finer spatial scale than the secondary compartments because the areas of higher coastal risk represent a higher proportion of the coast of interest. Higher coastal risk could be attributed to a higher proportion of susceptible natural structural features, such as cuspate forelands, and/or more unstable landforms, such as active dunes and scarped foredunes.

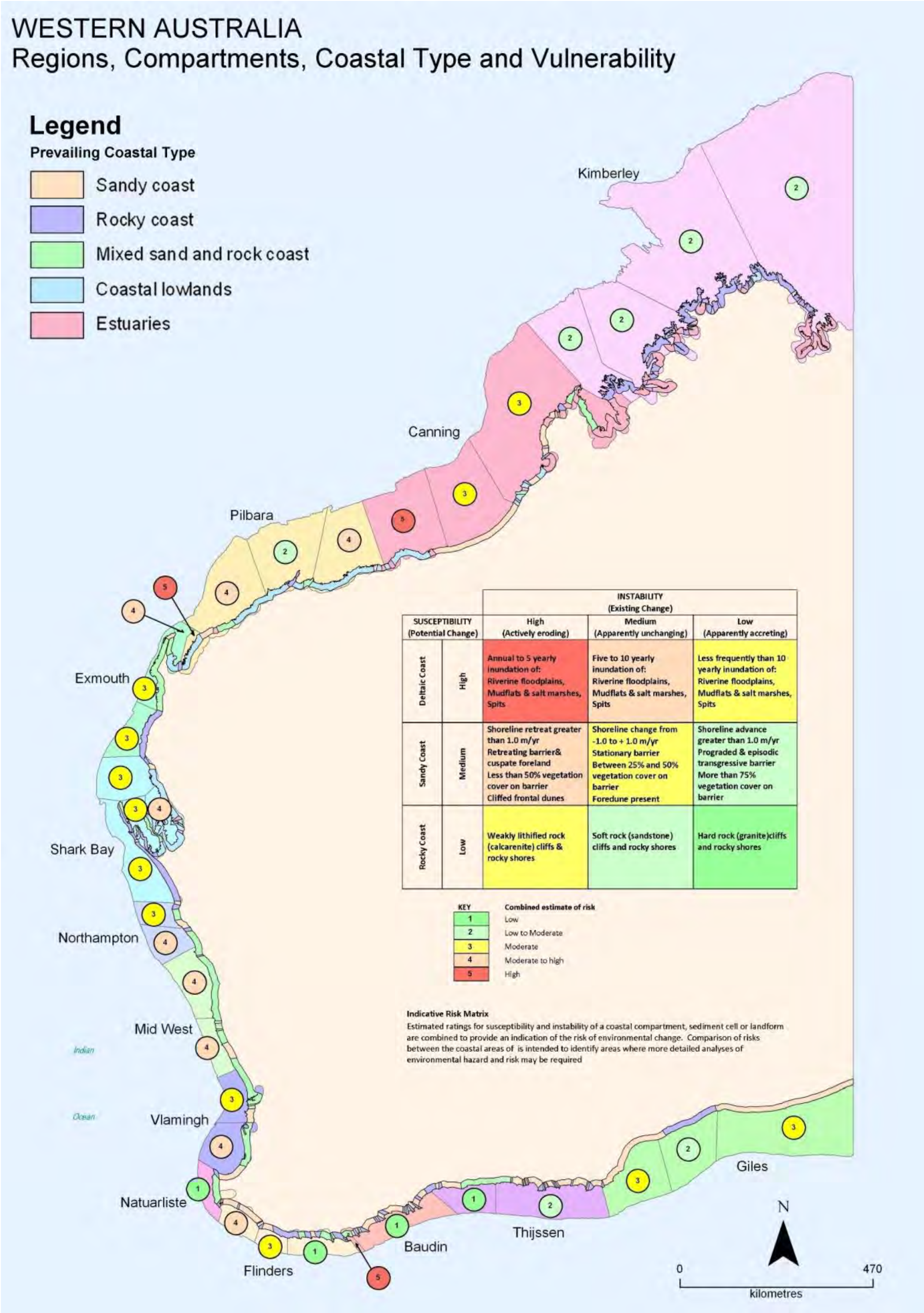


Figure 5-2: Coastal Types and Primary Compartment Vulnerability for Western Australia

There are three sets of information on this map: (1) The broad coloured strip map covering the nearshore waters indicates the coastal regions; (2) The narrow ribbon along the shore indicates the coastal type as per the legend and has been derived from the OSRA/WACoast databases; (3) The small coloured circles indicate coastal vulnerability (indicative risk) for each of the primary compartments. The colours in the circles are consistent with the colours in the indicative risk matrix.

The risk matrix considered very large scale land systems, particularly sandy, rocky and deltaic coastal systems relevant for a State-wide assessment of coastal vulnerability. This is the same approach as that used for consideration of the more detailed land systems of the Gascoyne coast shown in Figure 2-5.

(Source: Eliot *et al.* 2011).

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6. Areas of Planning Interest

Areas of Planning Interest are those under development pressure or have been identified for a proposed change to land use. Further information on relevant planning documents at regional and local scales is contained in a summary document prepared by the Department of Planning (2010).

This Section of the document provides an assessment of coastal landform vulnerability at a detailed scale for each Area of Planning Interest. Coastal management requirements are discussed and further studies that may be relevant at each site. The vulnerability analysis has been conducted at a sediment cell scale and therefore is indicative rather than prescriptive at the scale of landform elements (infrastructure or engineering scales). Planning information has been considered with respect to the general objectives of the *Coastal Zone Policy for Western Australia* (WAPC 2001) and the more specific guidance provided by Statements of Planning Policy (WAPC 2003, 2006).

Fifteen Areas of Planning Interest have been identified for the Shires of Shark Bay to Exmouth (Figure 1-1). These include:

- Nanga
- Denham area
    - Denham
    - Little Lagoon
- Monkey Mia
- Carnarvon area
    - Carnarvon
    - Miaboolya Beach
- Quobba-Blowholes area
    - Blowholes
    - Quobba Station
- Gnaraloo area
    - Red Bluff
    - Three Mile Camp
    - Gnaraloo Station
    - Gnaraloo Bay
- Coral Bay
- Vlamingh Head
- Exmouth

The more detailed vulnerability assessment for each Area of Planning Interest involved:

- Identification of the relevant sediment cells;
- Determination of the levels of susceptibility, instability and vulnerability across the cells. This included the identification of the landforms most at risk and other coastal constraints related to metocean forcing;
- Advice for coastal management; and
- Identification of relevant further studies.

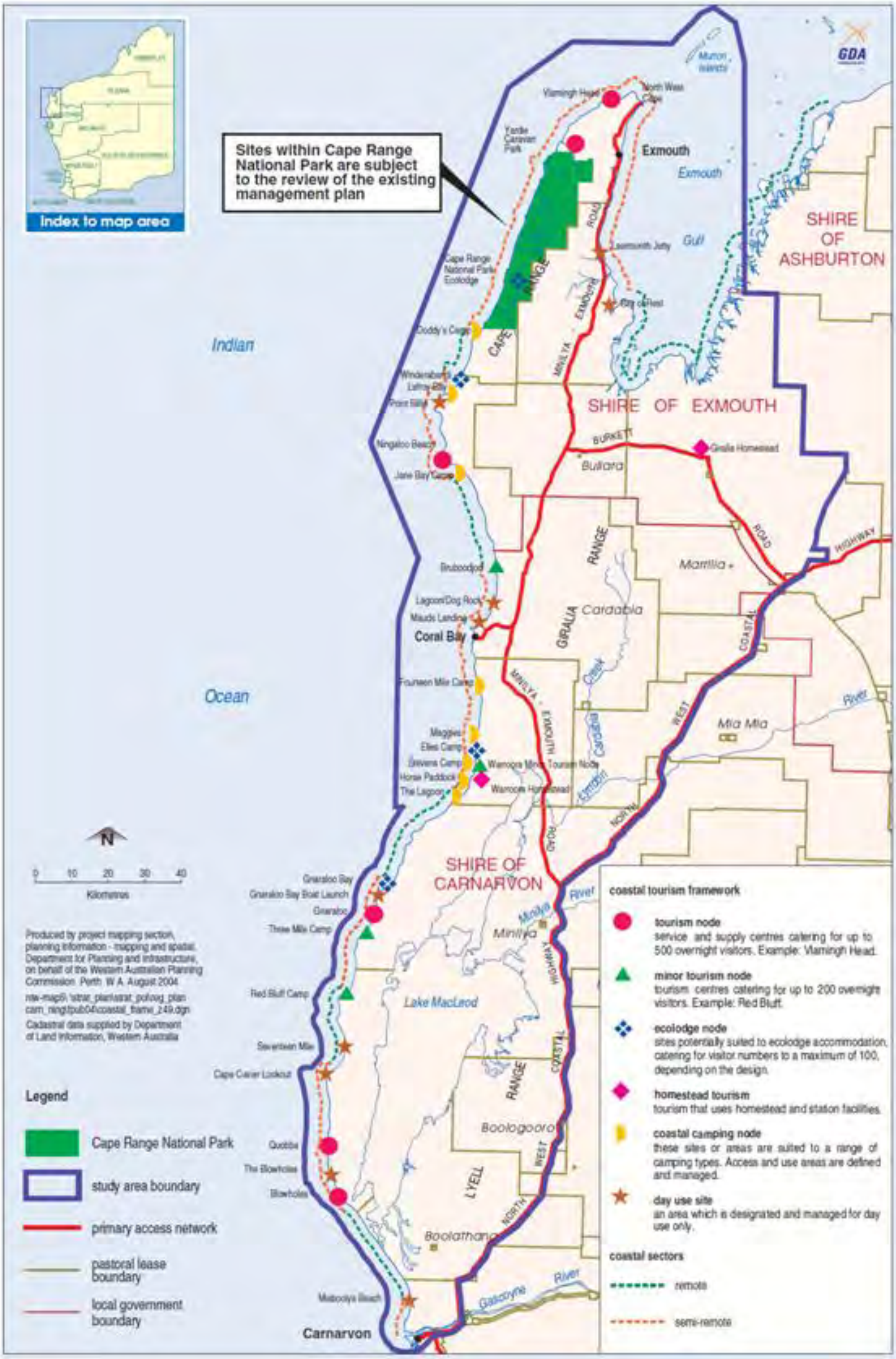

Figure 6-1: Coastal Tourism Framework for Ningaloo Coast Regional Strategy From Carnarvon to Exmouth (Source: DPI 2004)

The area from Carnarvon to Exmouth has additional planning requirements to *Statement of Planning Policy No. 2.6 – State Coastal Planning Policy* (WAPC 2003) and the *District Zoning Schemes* for Shires of Carnarvon and Exmouth (DoP 2009b, c) to be considered in any wider coastal management plans, site-specific structure plans or outline development plans. A further development control instrument is the *Statement of Planning Policy SPP No. 6.3 – Ningaloo Coast*, which outlines level of tourist development based on type and quantity of tourist accommodation (WAPC 2004; Figure 6-1).

All location names within the text are based on the following sources:

1. AUSLIG. (1993) *Topographic Series*, *1:100 000 Map Sheets for Western Australia.* Commonwealth Government, Canberra.
2. Geological Survey of Western Australia: GSWA. (2007) *Atlas of 1:250 000 Geological Series Map Images, Western Australia, April 2007 update*. GSWA, Perth.
3. Department of Transport and Australian Navy Navigation Charts. Index of Department of Transport (previously Department for Planning and Infrastructure and Department of Marine and Harbours) charts available at http://www.transport.wa.gov.au/mediaFiles/mar_chart_index.pdf.

6.1. NANGA

Nanga is located 53km southeast of Denham on the Peron Peninsula and in Henri Freycinet Harbour, western Shark Bay (Figure 1-1). Nanga is in the secondary compartment of Giraud Point to Goulet Bluff and in the sediment cell from Nanga Bay to Goulet Bluff (Cell 1).

Recent aerial imagery is shown in Figure 6-2; Oblique aerial photos in Figure 6-3; Landforms and vulnerability in Figure G-2; Landform instability in Table G-1; Cell description in Table G-2; Susceptibility, instability and vulnerability rankings are in Table G-3 and Table G-4, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

Figure 6-2 : Aerial Photography Nanga (2007)
Note: No historic aerial imagery for Nanga was readily available

Coastal susceptibility, instability and vulnerability

The cell has moderate susceptibility and low instability. There is a low-to-moderate vulnerability with coastal risks including alteration to the sediment supply potentially causing foredune plain retreat. Retreat of the beach and foredune is limited by the underlying cliff. The erosion threat presents a low constraint for coastal management.

Advice

Construction on the beach or foredune plain is likely to require significant management measures due to risk of inundation and retreat. Locating infrastructure landward of the scarp will significantly reduce the risk of landform inundation or retreat.

Any works that could potentially interrupt sediment transport along the terrace or the beachface will require consideration for the impacts on the adjacent coast with associated management measures. In addition these works, even if intended to be porous, may unintentionally impound seagrass wrack and shells further impeding sediment transport (eg. Peron Fence; Figure 6-4).

Figure 6-3: Nanga Obliques 16 May 2011
Source: WACoast (Gozzard 2012) and Ian Eliot

Figure 6-4: Sediment and Wrack Capture at Peron Fence 25 October 2006 (Source: Damara WA 2006e)

***Further studies*:**

The following studies could be used for a hazard and risk assessment and in any application of SPP No. 2.6 for Nanga.

1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique). The seaward extent of the scarp should be identified in the area covered by the ODP;
2. Resolution of key environmental processes, including locally generated wind waves and consideration of tropical cyclones and water levels. This could include the selection of a design tropical cyclone following advice within Damara WA (2009). Metocean forcing should be considered from multiple directions;
3. Identification of sediment sources, sinks and key transport pathways with a focus on the terrace behaviour. Consider the potential changes in sediment supply that could occur under changing metocean forcing, including behaviour of the terrace, and how the beachface and foredune plain may respond. The response of the terrace to long-term changes in environmental forcing and sediment supply is likely to be more informative than the vegetation line due to the importance in sediment transport along the terrace; and
4. Consideration of the mechanisms for terrace response and beach response to storm events and the longer-term non-linear response of these features to changes in sea level, in the context of the underlying rock and the sediment budget. Equilibrium-based cross-shore models (such as SBEACH) are unlikely to accurately simulate the storm response on this coast. Any acute storm response should also consider alongshore transport, with rock headlands providing coastal control.

6.2. DENHAM AREA

Two Areas of Planning Interest are located in the Denham townsite area: Denham (Section 6.2.1) and Little Lagoon (Section 5).

6.2.1. Denham

Denham is the main coastal townsite for the Shire of Shark Bay, located on the Peron Peninsula in Henri Freycinet Harbour, western Shark Bay (Figure 1-1). The town foreshore is in the secondary compartment of Goulet Bluff to Middle Bluff and in the sediment cell from Denham South to Lagoon Point (Cell 2).

Comparison of historic aerial imagery is shown in Oblique aerial photos in Figure 6-6; Landforms and vulnerability in Figure G-4; Landform instability in Table G-5; Cell description in Table G-6; Susceptibility, instability and vulnerability rankings in Table G-7 and Table G-8, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

Figure 6-5 : Aerial Photography Denham (1957 and 2007)

Figure 6-6: Denham Obliques 16 May 2011
East to West from Top to Bottom
Source: WACoast (Gozzard 2012)

Coastal susceptibility, instability and vulnerability

The cell has low susceptibility and low instability. Across the cell, there is a low vulnerability with risks including inundation and foredune plain retreat caused by alteration to sediment supply likely to provide low constraints to coastal management.

However, there are landforms within the cell that are more unstable and hence are likely to provide greater coastal planning constraint, such as the storm ridge and tidal flat on which the original townsite was constructed, including the reclaimed foreshore of Knight Terrace. This low-lying area will be prone to increased inundation and consequently shore retreat due to projected sea level rise. Without adequate adaptation, a rise in sea level and associated rise in groundwater levels may progress the landforms to a tidal flat similar to the coast north of the Oceanarium (Figure G-4; Figure 6-7).

In the absence of adequate engineered structures the storm ridge would migrate landwards during inundation events, with increased frequency due to higher sea levels. The rate of retreat is affected by the underlying rock structures, with low elevation or discontinuous rock features potentially enhancing rates of erosion. The subtidal terrace is also likely to rise and narrow in response to rising sea level with potentially altered rates of sand and shell supply from the adjacent seagrass beds and nett northerly sediment transport rates along the terrace and beachface (bar migration).

Figure 6-7: Tidal Flat Southeast of Denham
Corresponds to symbol *Tf* in Figure G-4
(Source: WACoast 16 May 2011. Gozzard 2012)

This is an engineered coast with coastal response affected by rock walling, foreshore reclamation, the harbour basin and channel.

- The presence of walling effectively prevents wave runup and provides increased foreshore stability under a range of design conditions. However, for storm events with a peak steady water level nearing the wall crest, overtopping must be managed via drainage to prevent catastrophic failure of the wall. Under projected sea level rise scenarios, this will require future adaptation of the foreshore walling. In addition, wave reflection from the wall can cause local scour and flanking erosion, potentially requiring progressive downdrift extension of the walling, unless connected to foreshore rock.

- Existing unprotected reclaimed areas north of the foreshore walling are susceptible to retreat because: they are located adjacent to walling and are subject to downdrift and flanking effects; the material is generally less compact than natural beach sediment; and the reclaimed areas directly experience wave action (Figure 6-8).
- The harbour and channel capture sediment transported along the terrace with the majority of sediment accumulating on the southern and southeastern areas, with some deposition in the southwest corner of the harbour and on the northwest corner adjacent to the boat ramp. Rates of dredging in the access channel and harbour are likely to change with sea level and consequent subtidal terrace response.

Figure 6-8: Denham Foreshore Rock Walling and Reclamation (Source: WACoast 10 May 2011. Gozzard 2012)

Advice

Further construction along Denham foreshore landforms including the foredune plain, foredunes and reclaimed foreshore areas (on sandstone outcrops) are likely to require significant management measures due to risks of inundation and coastal retreat. This includes the area seaward of the scarp which is east of the present limit of residential development, currently zoned for pastoral use. Potential inundation and flood mitigation requires increased consideration alongside aesthetics and visual landscape requirements. Construction landward of the scarp will significantly reduce the risk of landform inundation or retreat; however, this may reduce aesthetic and amenity values.

The existing policy of minimum building floor levels should also incorporate emergency management principles for safe evacuation route planning. Where foundations are used to raise floor levels, it is advised they be designed to sustain forces from inundation and wave loading during severe tropical cyclone events to minimise risk of catastrophic failure.

Any works that could potentially interrupt sediment transport along the terrace or the beachface require consideration of impacts on the adjacent coast and associated management measures. Such works, even if intended to be porous, may unintentionally impound seagrass wrack, further impeding sediment transport (eg. Peron Fence; Figure 6-4).

Consideration should be given to the nature and cost of future foreshore stabilisation works and plans for dredged material disposal. This should consider the extent of walling, maintenance costs, and requirements for overtopping drainage due to higher water levels. Raising the elevation of the walling above the land behind promotes ponding behind the structure during inundation events. Raising the walling will not prevent rising groundwater levels. It is advised that an adaptation plan be developed for the foreshore area with regard to potential changes in metocean forcing, particularly changes in sea level.

Further studies

A coastal hazard and risk is advisable for the Denham townsite. This information can then be used to develop future adaptation plans. The following studies may be used to inform the hazard and risk assessment:

1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique);
2. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and tropical cyclones;
3. Detailed consideration of tropical cyclones and water levels in relation to impacts on the reclaimed and foredune landforms and inundation levels. Tropical cyclones should be investigated for significant surge and strong winds along the longest fetch. This could be an extension of the work started in the wider area by GEMS (2009) and Damara WA (2009), with site specific applications at Denham;
4. Determination of a sediment budget based on the identification of sediment sources, sinks and key transport pathways with a focus on the terrace behaviour. This would include consideration of the impact of the maritime facility, reclamation activities since the 1840s, walling and any future proposals to modify the coastal sediment budget. It should be noted that vegetation lines may not demonstrate long term coastal change due to the subtidal terrace structure, long-term reclamation, historic disposal of dredged material and the presence of walling. Bathymetric soundings and dredging records could be used in understanding the terrace behaviour, in conjunction with records of dredge material disposal; and
5. Consideration of the mechanisms for terrace response, storm bar retreat and beach response to storm events and the longer-term non-linear response of these features to changes in sea level. This should be considered in the context of the underlying rock structure and the presence of walling. Cross-shore equilibrium-based models (such as SBEACH) are unlikely to accurately simulate the storm response on this coast as they do not incorporate alongshore transport. Projected long-term changes should be considered for the terrace, foredune plains and foredunes.

6.2.2. Little Lagoon

Little Lagoon is within the Denham townsite, 5km north of the town centre, on the Peron Peninsula (Figure 1-1). Little Lagoon is in Henri Freycinet Harbour, western Shark Bay. Little

Lagoon is located in the secondary compartment of Goulet Bluff to Middle Bluff and in the sediment cell from Lagoon Point to Middle Bluff (Cell 3).

Comparison of historic aerial imagery is shown in Figure 6-9 and Figure 6-10; Oblique aerial photos in Figure 6-11; Landforms and vulnerability in Figure G-4; Landform instability in Table G-5; Cell description in Table G-6; Susceptibility, instability and vulnerability rankings are in Table G-7 and Table G-8, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

Coastal susceptibility, instability and vulnerability

The cell has moderate susceptibility and moderate instability. There is a moderate vulnerability with risk of inundation presenting the most likely constraint for coastal management, exacerbated by sea level rise. Further coastal risk of altered sediment supply may present a moderate constraint to coastal management.

Little Lagoon is a tidal creek, the precursor to a Birrida, connected to the ocean through tidal flats with the mouth located in a 3km long and approximately 250m wide chenier and spit plain, constrained by the present of rock. There is nett alongshore transport to the north with recurved spits and cheniers, diverting the mouth to the north (Figure 6-10). This area has a 2km wide sub-tidal terrace with sand ridges, bars and small spits close to shore.

The recreational use adjacent to Little Lagoon may increase as the population and number of tourists increase for Denham. At present, there are two main access car parks on the east, a system of three car parks along the channel in the tidal flats and a car parking area at the southern extent of the chenier and spit plain (Figure 6-11; Figure 6-12). There are a number of off-road vehicle access tracks abutting the tidal flats and chenier and spit plain, as well as tracks within these landforms to the north of the Lagoon entrance (Figure 6-12). Some of the low-lying carpark areas and tracks are at risk of inundation under higher sea levels, creating potential future infrastructure and public safety issues.

There are two locations where informal boat launching is occurring, at the southern end of the chenier and spit plain and further north where the boat launching has generated a breach across the cheniers and created a shallow channel across the tidal flats (top two images in Figure 6-12). This breach and channel create a zone of locally enhanced instability, particularly in the event of a high energy storm. This could increase the rate of retreat of the chenier and spit plain to the north of the breach.

Landward migration of the cheniers and spits is expected occur due to overwash associated with projected sea level rise. Wholescale retreat of areas of the chenier and spit plain could occur if there was a decrease in sediment supply combined with higher sea levels.

The lagoon entrance is a local area of instability, affected by tidal exchange, runoff under extreme events and sediment supply (Bruun & Gerritsen 1960). Future response of the entrance is uncertain, as both tidal exchange and sediment supply are anticipated to increase under projected sea level rise. Over inter-decadal or longer time scales there is risk of lagoon entrance blockage, potentially turning the lagoon into a Birrida if there was insufficient exchange or cross-shore erosion to overcome the rate of alongshore sediment supply (Bruun & Gerritsen 1960). Alternatively there could be a further northwards migration of the mouth. Tidal flat migration will occur in response to changes to the mouth.

Figure 6-9 : Aerial Photography Little Lagoon (1957 and 2007)

Figure 6-10 : Aerial Photography Little Lagoon Finer Scale

Advice

Inundation is a constraint for any plans for site access and day use infrastructure at Little Lagoon. Access may need to be managed for off-road vehicles, including restrictions on boat launching within the chenier and spit plain. An accepted level of risk of storm inundation is recommended for any infrastructure adjacent to Little Lagoon, including car parks and shelters. Temporary or transportable infrastructure could be moved with rising sea levels, accepting the risk of storm surge.
The potential modification to sediment supply should be considered in a risk assessment context.

Figure 6-11: Little Lagoon Obliques 16 May 2011

South to North from Top to Bottom
Source: WACoast (Gozzard 2012) and Ian Eliot

Figure 6-12: Some of the Car Parks, Access Locations, ORV Tracks and Unofficial Boat Launching Locations Adjacent to Little Lagoon
Source: WACoast (Gozzard 2012)

Further studies

A risk assessment should contribute to strategic plans for access management and installation of any infrastructure. The two main coastal process studies that would benefit the assessment are: (1) a storm inundation study; and (2) a sediment budget investigation including sediment transport pathways and volumes in relation to tidal channel restriction and landform mobility with sea level rise.

The second study could consider the general approach of Bruun & Gerritsen (1960) to determine if the mouth is likely to stay open under different scenarios of the tidal prism to the approximate gross annual rates of alongshore sediment transport. This could be investigated for a range of potential sediment transport rate scenarios and for present and projected sea levels over time frames suitable for any proposed infrastructure (refer to DoT 2010). Sediment transport rates should consider gross and nett transport and the capacity for response to changing metocean forcing. The sediment available for northward alongshore sediment transport may increase with rising sea levels as sediments are mobilised from the chenier and spit plain to the south of the mouth. This study should also consider the potential erosive capacity of storm events for present and projected sea levels.

6.3. MONKEY MIA

Monkey Mia is a tourist settlement, located 25 km from Denham on the north side of the Peron Peninsula within the eastern arm of Shark Bay (Figure 1-1). Monkey Mia is at the northern extent of L'Haridon Bight, adjacent to the Herald Gut Channel between Monkey Mia and Faure Island (Butcher *et al.* 1984; Playford 1990). Monkey Mia is on the boundary of the secondary compartments of Cape Peron North to Monkey Mia and Monkey Mia to Petit Point, and the primary sediment cells of Cape Rose to Monkey Mia and Monkey Mia to Dubaut Point. Monkey Mia is also a boundary of the two secondary cells considered in this study from Red Cliff Bay to Monkey Mia (Cell 4) and Monkey Mia to Eastern Bluff (Cell 5).

Comparison of historic aerial imagery is shown in Figure 6-13 and Figure 6-14; Oblique aerial photos in Figure 6-15; Landforms and vulnerability in Figure G-6; Landform instability in Table G-9; Cell description in Table G-10; Susceptibility, instability and vulnerability rankings are in Table G-11 and Table G-12, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

Coastal susceptibility, instability and vulnerability

Both cells adjacent to Monkey Mia have moderate susceptibility with low instability; however, Cell 5 has higher instability as indicated by the rounded beach profile and is more exposed to enhanced tidal currents in the Herald Gut Channel between Monkey Mia and Faure Island. There is a low-to-moderate vulnerability with risks including inundation; and foredune plain retreat in the vicinity of the settlement due to variability of sediment supply. If properly addressed, these risks are likely to present a low constraint for coastal management.

In non-tropical cyclonic conditions there is alongshore sediment transport on the terrace indicated by the shore normal bars west of the settlement. As sediment supply increases the foredune plain may accrete in ridges along the shore, largely due to the recurving of sediment spits towards the coast and reworking by storm events (e.g. suggested by the series of ridges in Figure 6-15). For example, a spit is presently migrating northwards and recurving along the terrace of Cell 5 towards Monkey Mia. Over time this will recurve toward the shore and this could continue building out the east side of the foreland. This could modify sediment transport rates around the tip of the foreland and alter terrace behaviour. If sediment supply were to decrease the foredunes may strip with the most recently accreted areas likely to be the ones that retreat.

A tropical cyclone has the potential to inundate the settlement under present sea levels and to mobilise sediment, with the likelihood of inundation increasing under projected sea level rise. With the majority of the settlement located below 3m AHD. These locations are at risk of coastal flooding and inundation. In addition to causing inundation, a tropical cyclone could also temporarily mobilise a large volume of sediment, stripping the beach and foredune plain elevations to the base of the underlying rock, particularly in the vicinity of the tip of the foreland.

Figure 6-13 : Aerial Photography Monkey Mia (1957 and 2007)

Figure 6-14: Aerial Photography Monkey Mia Finer Scale

Figure 6-15: Monkey Mia Obliques 16 May 2011
Source: WACoast (Gozzard 2012)

The groundwater level will rise with sea level, reducing the drainage capacity during inundation events and increasing the risk of ponding. This is particularly relevant in the lowest elevation areas that are <0.5mAHD.

The most significant coastal threat at Monkey Mia is the risk of foredune plain mobilisation due to projected sea level rise, compounded by storm events, resulting in landform retreat across the foreland. This is dependent on the rate of sediment supply to the foreland from the south and potential for high water levels to overwash and breach the eastern foredunes. The tip of the foreland is constrained by the presence of rock at approximately present day mean sea level. This control will decrease with projected sea level rise. Extreme water levels could breach the high foredunes on the eastern side of Monkey Mia, inundating the low-lying land behind which would provide a tipping point for rapid landform migration and retreat. If there is high sediment supply (which can increase with higher water levels as adjacent coasts are eroded) the likelihood of dramatic retreat is reduced, although slower landward migration of the foredunes towards the resort development is anticipated.

Advice

The existing policy of minimum building floor levels should incorporate emergency management principles for safe evacuation route planning. Where foundations are used to raise floor levels, they should be designed to sustain forces from inundation and wave loading during severe tropical cyclone events to minimise risk of catastrophic failure.

An adaptation and management plan may be required in the vicinity of the present development in the context of anticipated retreat with climate change. Management plans may include beach nourishment as no hard structures are presently permitted (EPA 2005).

Any works that could potentially interrupt sediment transport along the terrace or the beachface will require consideration for the impacts on the adjacent coast with associated management measures. In addition these works, even if intended to be porous, may unintentionally impound seagrass wrack further impeding sediment transport (eg. Peron Fence; Figure 6-4).

Further studies

A coastal hazard and risk assessment should be conducted for Monkey Mia. This information can then be used to develop future adaptation plans. The following studies may be used to inform the hazard and risk assessment:

1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique);
2. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and tropical cyclones;

3. Detailed consideration of tropical cyclones and water levels in relation to impacts on the terrace and foredune landforms and inundation levels. Tropical cyclones should be investigated for significant surge and strong winds along the longest fetch. This could be an extension of the work started in the wider area by GEMS (2009) and Damara WA (2009), with site specific applications at Monkey Mia;
4. Identification of sediment sources, sinks and key transport pathways with a focus on the terrace and foredune behaviour and connectivity. This would include consideration of any dredging for the jetty operations and if any future proposals could significantly modify the coastal sediment budget. This should consider the potential changes in sediment supply that could occur under metocean forcing seasonally, inter-annually, during a tropical cyclone and over the longer-term with climate change.
5. Consideration of the mechanisms for terrace response, storm bar retreat, beach and foredune response to storm events and the longer-term non-linear response of these features to changes in sea level in the context of the sediment budget and presence of rock. The model SBEACH is unlikely to accurately simulate the storm response on this coast and does not consider alongshore transport on the terrace.

6.4. CARNARVON AREA

Two Areas of Planning Interest are located in the Carnarvon area: Carnarvon (Section 6.4.1) and Miaboolya Beach (Section 6.4.2).

6.4.1. Carnarvon

Carnarvon is the regional centre of the Gascoyne, and the main townsite for the Shire of Carnarvon. It is located at the north of Shark Bay and south of the Ningaloo coast (Figure 1-1). Carnarvon townsite is located in the secondary compartment of Grey Point to South Bejaling Hill and is largely located in the sediment cell from Massey Bay to Gascoyne River South (Cell 6), with consideration required of the Gascoyne River and the sediment cell from Gascoyne River South to Gascoyne River North (Cell 7).

Comparison of historic aerial imagery is shown in Figure 6-16 to Figure 6-18; Oblique aerial photos in Figure 6-19; Landforms and vulnerability in Figure G-8; Landform instability in Table G-13; Cell description in Table G-14; Susceptibility, instability and vulnerability rankings are in Table G-15 and Table G-16, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

Coastal susceptibility, instability and vulnerability

The cell containing Carnarvon townsite has high susceptibility and high instability, with a similar rating to adjacent cells within the Gascoyne River delta. High vulnerability is related to the risk of tropical cyclonic inundation and overtopping; river flooding and altered sediment supply. River flooding may cause river channel migration or bank retreat and modify sediment supply to the adjacent coast. Flooding has a high risk of causing landform inundation (including washover), migration, deflation, erosion or accretion. This is relevant to the low-lying landforms of tidal flats, mangal flats, delta plain, alluvial plains, strandplains, river channels, foredunes, spits and sand islands (Figure G-8; Table G-13). The level of risk is a major constraint for coastal management.

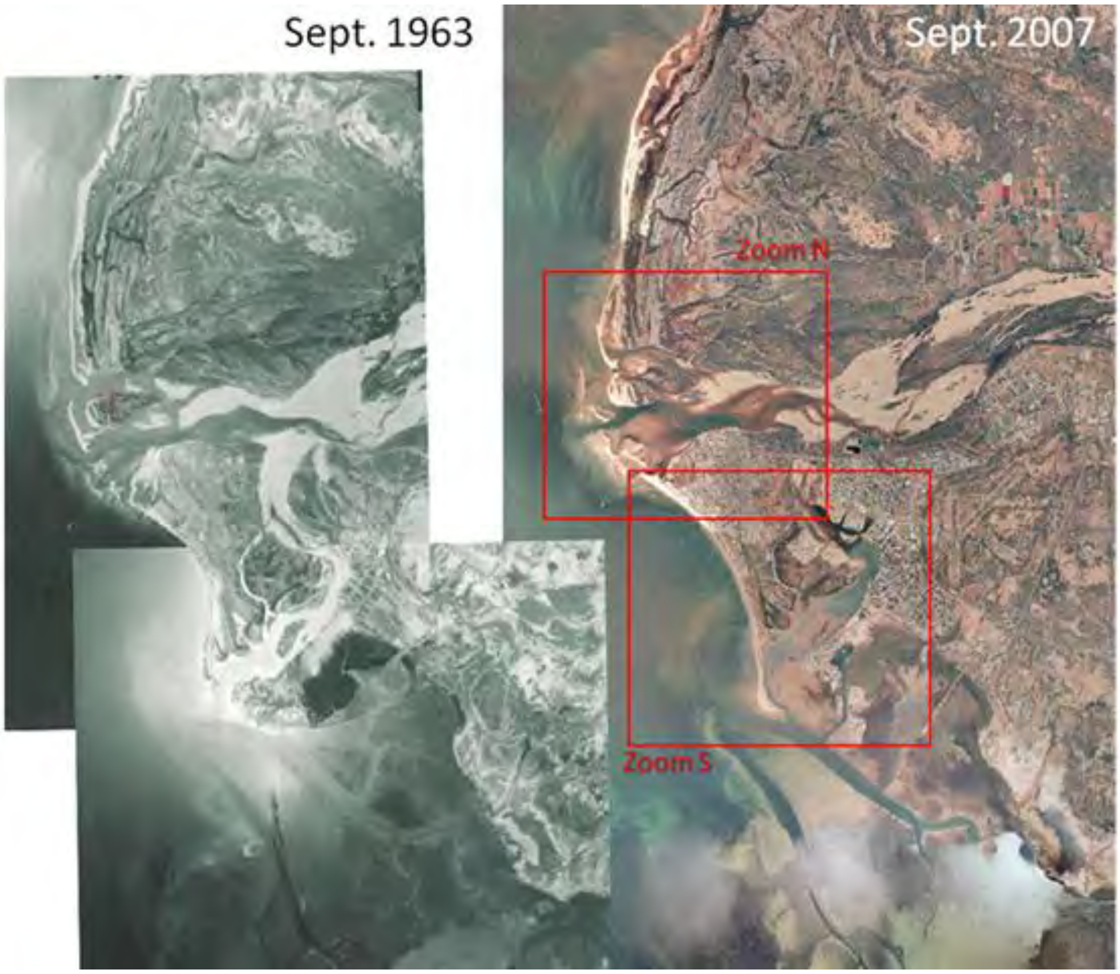

Figure 6-16 : Aerial Photography Carnarvon (1963 and 2007)
Areas shown in red boxes are shown at a finer spatial scale in Figure 6-17 and Figure 6-18

Figure 6-17 : Aerial Photography Carnarvon Zoomed South

Figure 6-18 : Aerial Photography Carnarvon Zoomed North

Risk of tropical cyclone inundation and potential coastal response, based on present coastal alignment and engineering works, is considered in GEMS (2009). The GEMS (2009) study divided the area into shore types. Process-based models were derived for each shore type, following the division of acute erosion, chronic erosion and sea level rise allowances used by SPP No. 2.6 (WAPC 2003), and targeting the key elements of possible future climate impacts. The shore types considered were: riverine landforms, sand dunes, barrier spits, the Fascine Basin, sand flats, walling structures, tidal spits, tidal creeks, mangroves, and combined mangroves and walling. These are consistent with the landforms used in this report, with the addition of walled shore types. Further information on risks for each shore type should be obtained from the GEMS (2009) document.

Flood risk of inundation is presented in SKM (2002), which predated the December 2010 floods (BoM 2011). The flooding capacity of the Gascoyne River and relative significance of the 2010 floods is included in Section 4.4.5. Finished floor levels of 4.2mAHD were recommended for Carnarvon in the *Gascoyne Coast Regional Strategy* (WAPC 1996), with revision required (DPI 2004). In the near future the level may be based on an accepted level of risk using the information within the SKM (2002) and GEMS (2009) studies.

Any coastal or river modification has the potential to transfer risk to the adjacent coasts. The geomorphic response of the river channel and adjacent foreshores is discussed in GEMS (2009). For example, creation of a hardened section of river foreshore may either reduce the stability of the opposite bank, or may cause the channel deepen locally during strong flood events, affecting the flanking shore. Historic behaviour has involved progressive erosion of the south bank of the river and westward movement of the ocean shore along Babbage Island. Between 1882 and 1974 the south bank eroded approximately 300m and the Babbage Island ocean shore migrated up to 500m westward. There has been sediment accumulation to the north of Whitmore Island during the past 50 years (Figure 6-18). In view of these changes there is a risk that infrastructure is insufficiently designed to account for loading by environmental forcing, associated landform response or the impacts of adjacent engineering works.

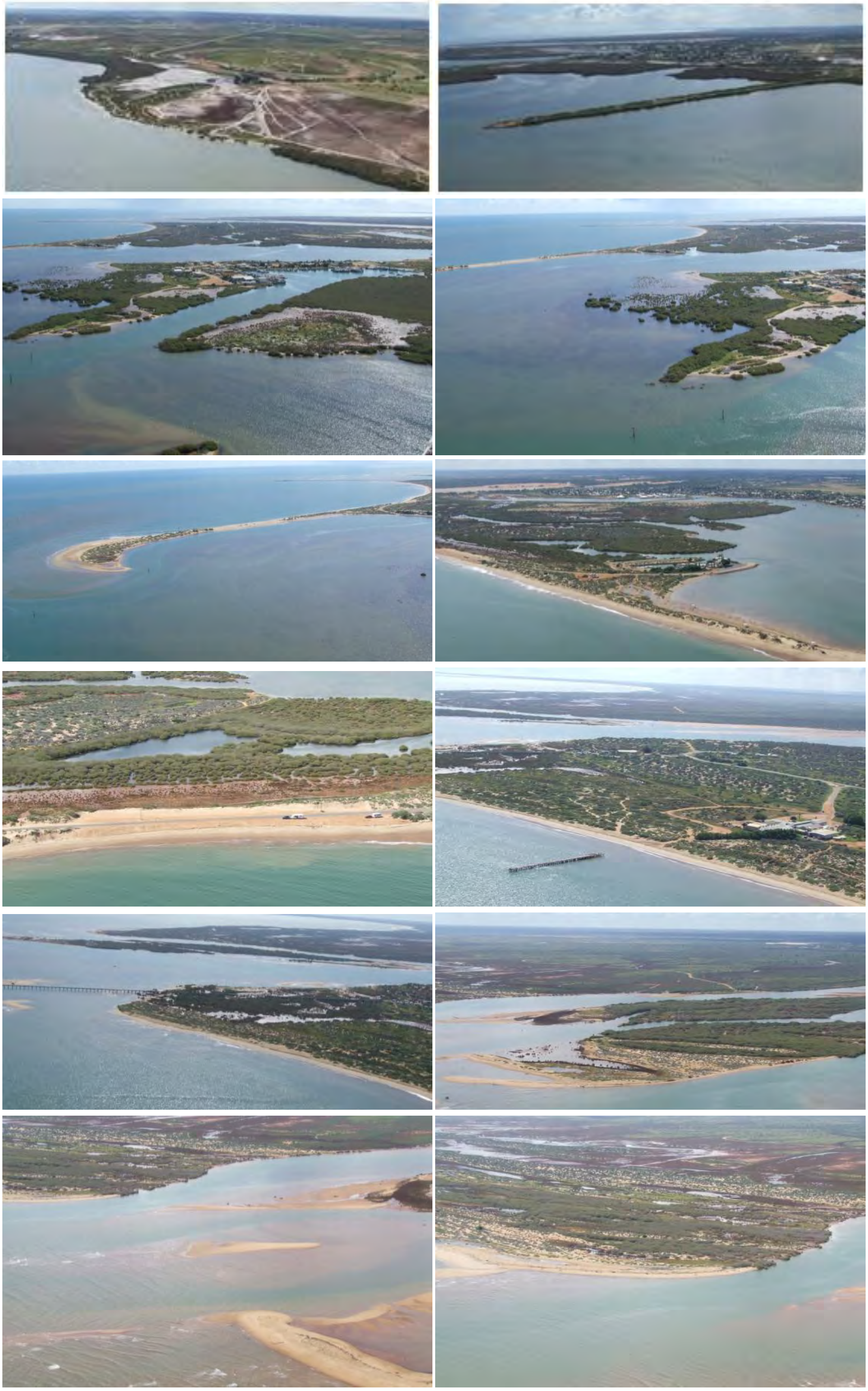

Figure 6-19: Carnarvon Obliques 16 May 2011
South to North from Top Left to Bottom Right. Source: WACoast (Gozzard 2012)

Advice
Future coastal management and planning could incorporate the potential coastal response of each shore type as reported in GEMS (2009). Connectivity should be considered with estimation of how a proposed coastal or river modification has the potential to transfer risk to the adjacent coasts. This may require detailed determination of the coastal sediment budget and analysis of landform change as a basis for validation of numerical models.

Carnarvon is susceptible to extreme flooding from tropical cyclones and river flooding, and cannot solely rely upon the use of coastal setbacks or existing coastal defences to provide a high level of hazard mitigation. A number of options could be considered to mitigate inundation and flood risk including:

- A flood emergency management plan;
- Coastal hazard and risk assessments, including a definition of acceptable risk, on a case-by-case basis;
- Raise walling around the town to a defined minimum level to mitigate risk of tropical cyclone inundation of low-lying areas of South Carnarvon;
- Locate critical town facilities outside identified areas of flood risk;
- The effectiveness of walling may be enhanced by controlling drainage of overtopping with consideration of rainfall; and
- Encourage construction of housing that is less susceptible to damage during an extreme event.

Further studies

Further assessment is recommended for the coastal flooding mitigation options in GEMS (2009).

Future plans for Carnarvon require a hazard and risk assessment per site, including a definition of acceptable risk, based on the findings of the GEMS (2009) and SKM (2002) studies. This should also include assessments of loading and geomorphic response, account for variations of sea levels associated with tidal cycles and mean sea level fluctuations, and consider impacts of any flood or inundation mitigation works on adjacent sites and across wider sediment cells. Planning for facilities with extended design life should have a greater allowance for sea level rise and flood risk (GEMS 2009).

It is recommended that the flood risk be reviewed on a 10-year basis for three reasons of:

- Uncertainty with climate change projections (GEMS 2009);
- Flood risk implications of surge and flood mitigation and management techniques; and
- Flood risk implications of changes to the geomorphology.

6.4.2. Miaboolya Beach

Miaboolya Beach day use site is located immediately 12km north of the Carnarvon townsite, north of the Gascoyne River mouth and Miaboolya Creek mouth (Figure 1-1). It is located in the secondary compartment of Grey Point to South Bejaling Hill and is located in the sediment cell from Gascoyne River North to Miaboolya Beach (Cell 8), with consideration required of the sediment cell from Gascoyne River South to Gascoyne River North (Cell 7).

Comparison of historic aerial imagery is shown in Figure 6-20 and Figure 6-21; Oblique aerial photos in Figure 6-22; Landforms and vulnerability in Figure G-8; Landform instability in Table G-13; Cell description in Table G-14; Susceptibility, instability and vulnerability rankings are in Table G-15 and Table G-16, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

Coastal susceptibility, instability and vulnerability

The cell containing Miaboolya Beach has high susceptibility and high instability, with a similar rating to the two cells to the south within the Gascoyne River delta. The combination of susceptibility and instability provides a major constraint for coastal management or development at Miaboolya. High vulnerability with is related to the high risk of tropical cyclonic inundation and washover, exacerbated by projected sea level rise; terrestrial flooding; migration of the tidal creek channel; and altered sediment supply. An increased sediment supply could result in extended closure of the tidal creek channel. A decreased sediment supply could result in beach and foredune erosion. Changes in sediment supply will be strongly influenced by projected sea level rise.

The cell is part of the northern flank of the Gascoyne River delta with associated landforms including a subaqueous delta, fronting a complex of chenier spits and foredune ridges. The landforms also include local-scale features, with a large tidal creek linked to the surface drainage system forming a breach through the foredune ridges. The creek is landward of a chenier spit and dune ridge, with episodes of increased nett northerly sediment supply creating a system of low-lying lagoons. The backshore deltaic environment includes cheniers, beach ridges, supratidal and intertidal flats, tidal creeks, runoff channels, palaeochannels and shallow basin swamps (Figure G-8; Table G-13; Table G-14).

There has been nett accretion of the beach and foredune between 1964 and 2007 (Figure 6-20; Figure 6-21), that has also coincided with the westward growth of Whitmore Island and Whitmore Point (Figure 6-16 and Figure 6-18).

The creek mouth can be temporarily closed by the deposition of sediment by wave forcing during periods of high nett sediment supply and low to no surface flow. This sediment may be released during significant surface runoff events or cross-shore erosion and inundation events, with migration of the mouth when it reopens. The beach and foredune will go through periods of growth dependent on sediment supply from the Gascoyne River and modification of the deltaic and chenier/spit landforms on the northern section of the delta, including the recurved spits in Cell 7. When the mouth is open, the creek may capture sediment from the coastal system, particularly after runoff flooding has ceased, or during periods of low tidal flow. During these conditions sediment supply north of the creek mouth is reduced, with rates increased once the mouth closes, allowing sediment to bypass.

The greatest potential human risk is due to inundation and washover of roads and car parks during coastal flooding or river flooding events. This is followed by the potential northward migration of the channel encompassing the day use car park. A further risk to the amenity of the site is the potential retreat of the recent beach accumulation due to a reduction in sediment supply from the south, particularly combined with shoreline retreat due to projected sea level rise.

Potential alteration in rates of sediment supply from the south is dependent on channel forming floods and the flood mitigation options for the Gascoyne River, such as extension of levee walls.

Figure 6-20 : Aerial Photography Miaboolya Beach (1964 and 2007)

The tidal creek entrance is at risk of blockage or migration with changing surface drainage forcing and increased rates of sediment supply. The entrance could be blocked if the surface drainage patterns altered due to channel blockage or avulsion, with less flow through the tidal creek channel, combined with increased rates of sediment supply from the south. This would eventually result in the creek becoming an enclosed lagoon if there was an insufficient flood event or cross-shore erosion event to exceed the rate of alongshore sediment transport (Bruun & Gerritsen 1960). Alternately, reduced sediment supply may cause further northwards migration of the mouth. Tidal flat and mangal flat migration will occur in response to changes to the mouth.

Advice

Inundation from coastal flooding, washover, river flooding and potential northward migration of the tidal creek channel is a constraint for any plans for site access and day use infrastructure. Access management is required for off road vehicles, to increase foredune stability. A clearly identified and accepted level of risk of terrestrial flooding, storm surge inundation, wave runup and washover is recommended for any infrastructure adjacent to Miaboolya Beach, including car parks and shelters. Temporary or transportable infrastructure could be moved with rising sea levels, long-term beach and foredune retreat or northward migration of the tidal creek channel, accepting the risk of storm surge.

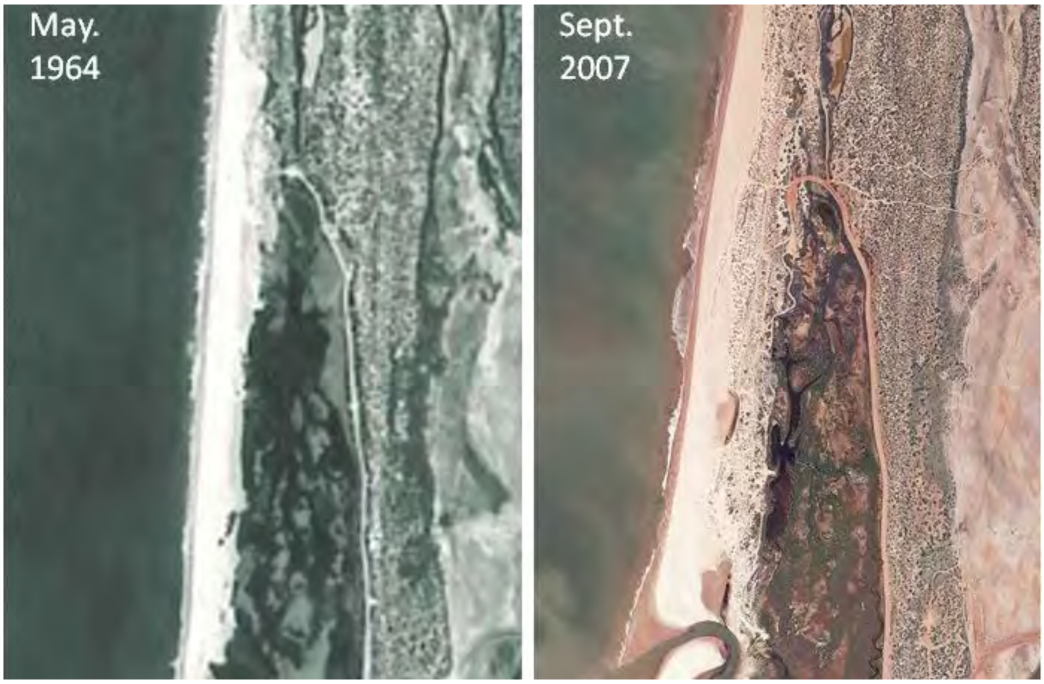

Figure 6-21 : Aerial Photography Miaboolya Beach Finer Scale

The potential change to sediment supply should also be considered in a hazard and risk assessment framework. Identification of site access constraints and adaptation plans may need to be developed according to the flood mitigation techniques adopted for Carnarvon townsite as these are likely to affect the sediment supply, flooding significance and potential shoreline position. Adaptation may be required if there is increased sediment supply and northward migration of the tidal creek channel.

Figure 6-22: Miaboolya Beach Obliques 16 May 2011
South to North from Top to Bottom
Source: WACoast (Gozzard 2012)

Further studies

A hazard and risk assessment should be conducted for the development of strategic plans for access management and the installation of any infrastructure. This assessment would benefit from information on storm surge inundation and wave runup and terrestrial flooding (GEMS 2009; SKM 2002). It would also benefit from a sediment budget investigation including potential transport and supply from the south in relation to potential beach retreat; or in relation to potential tidal creek restriction and northward migration of the creek mouth toward the day use car park. Analysis of potential for tidal creek constriction could follow the method suggested for Little Lagoon (Section 5) with scenarios of potential reduction in surface flow or tidal exchange through the creek.

6.5. QUOBBA-BLOWHOLES AREA

Two Areas of Planning Interest are located in the Quobba-Blowholes area: Blowholes (Section 6.5.1) and Quobba Station (Section 6.5.2).

6.5.1. Blowholes

Blowholes tourist node is located south of Point Quobba, 55km northwest of Carnarvon (Figure 1-1; Figure 6-1). It is at the northern end of the Gascoyne primary compartment and the secondary compartment from South Bejaling Hill to Point Quobba. It is in the northern half of the sediment cell from Fitzroy Reefs to Point Quobba (Cell 9).

Comparison of historic aerial imagery is shown in Figure 6-23; Oblique aerial photos in Figure 6-24; Landforms and vulnerability in Figure G-10; Landform instability in Table G-17; Cell description in Table G-18; Susceptibility, instability and vulnerability rankings in Table G-19 and Table G-20, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

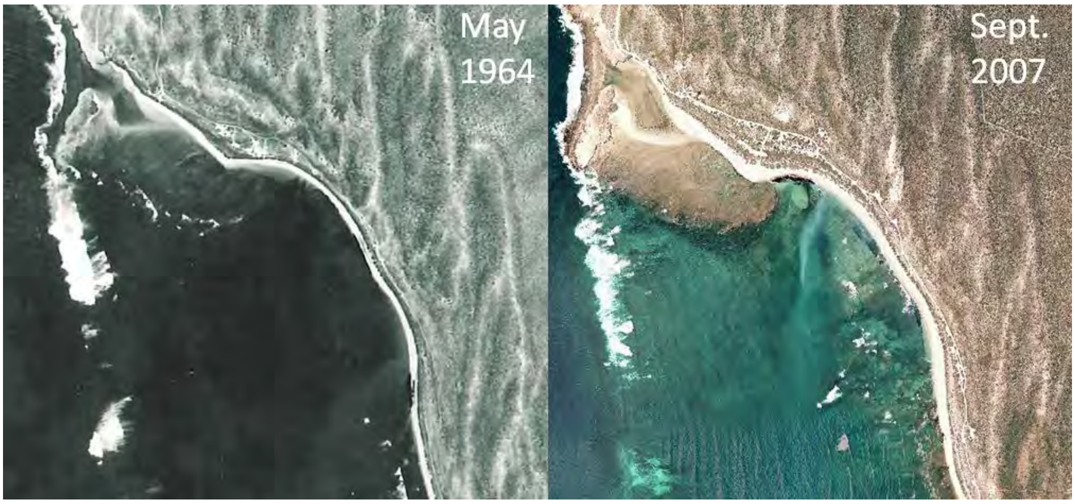

Figure 6-23 : Aerial Photography Blowholes (1964 and 2007)

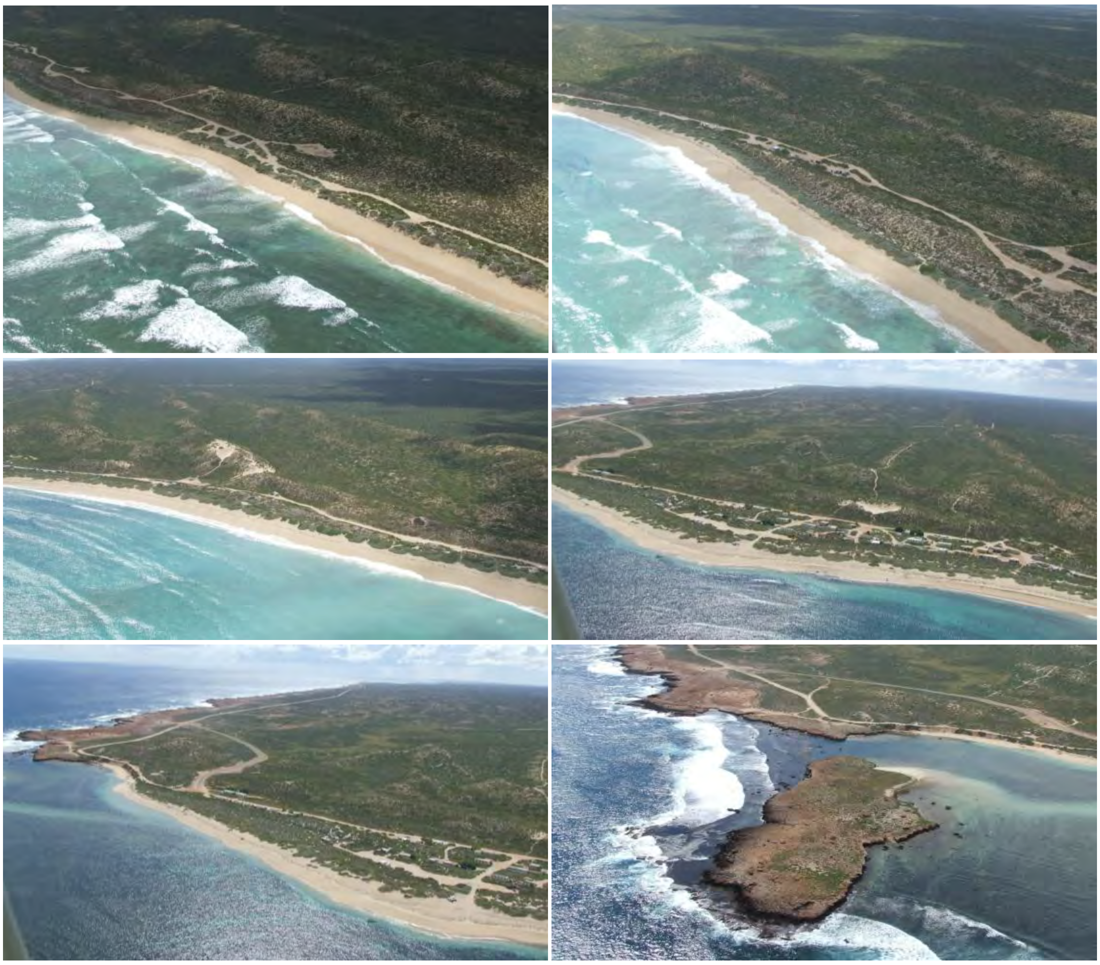

Figure 6-24: Blowholes Obliques 16 May 2011
South to North from Top Left to Bottom Right
Source: WACoast (Gozzard 2012)

Coastal susceptibility, instability and vulnerability

The cell containing the Blowholes has moderate susceptibility and moderate instability, producing a moderate vulnerability. Constraints to coastal management and development are moderate, requiring consideration of coastal inundation, salient retreat or migration, foredune retreat and potential coastal reatreat due to variation of sediment supply from the south. There is a higher risk of inundation in the hind-dune flat of the designated chalet area based on tropical cyclone surge modelling (GEMS 2006; Hames Sharley 2008).

The site is at inundation risk from the passage of a tropical cyclone or from tsunami. A tropical cyclone can also cause wind damage, wave impact, beach erosion and wave runup. Areas susceptible to inundation by peak steady water level due to passage of a 'design' Category 5 tropical cyclone coincident with high water spring tide and 0.38m sea level rise (GEMS 2006). Wave runup provides an additional risk to loss of human life and structural damage above the peak steady water level. Tsunami also provides an identified risk at Point Quobba due to local bathymetric focusing, according to modelling of tsunami propagation scenarios (Section 4.2.2.1).

The Blowholes salient is an unstable local feature, which can potentially retreat or migrate in response to extreme events, sea level rise and the change in inshore wave climate associated with sea level rise. These changes in environmental forcing at the Blowholes could also cause a reduction in beach width and potentially erode the foredunes. Some historic variability in the Blowholes salient and beach widths is demonstrated in Figure 6-23.

The Blowholes site is at the northern extent of a primary compartment and sediment cell. The beach, foredunes, foredune plains and dunes are influenced by the rate of sediment supply from the south. If the supply was reduced, whether by reduced supply from the strandplain or increased loss to blowouts, there would be narrowing of the beach and potential foredune erosion (Figure 6-25). If the supply was increased, by mobilisation of sediment from the strandplain under higher sea levels, this could lead to accretion, foredune growth, increase in beach width and increased wind-blown sediment transport through the settlement.

Figure 6-25: Evidence of Recent Foredune Retreat at Blowholes (Source: Ian Eliot 12 May 2011)

The greatest existing risk is the inadequate capacity of terrestrial infrastructure seaward of the setback line for physical processes and areas susceptible to inundation and wave runup. If retreat or inundation occurs there is likely to be ongoing costs for management and replacement of infrastructure. Additionally, there is a risk to human life and well-being during extreme storm and flood events.

Natural hazard from 'rogue' or 'king' waves occurs at Blowholes due to the proximity of deep water to a shallow rock platform. This is not explicitly a planning hazard, but should be recognised when considering recreational zones.

Advice

Risk management and adaptation to mitigate coastal hazards requires planning for reduction of the risks over the full planning time frame. This is especially so in consideration of decisions about coastal land subject to potential inundation and flooding associated with extreme events such as the passage of a tropical cyclone or a tsunami. Development on land subject to inundation requires consideration of the risk of direct inundation, wave action, wave pressures, scour, flooding of septic tanks, salt water damage, run-off induced channel formation, flooding of interdunal swales and lowering of the frontal dune elevation (GEMS 2006). The last of these increases the susceptibility to further inundation. Some of these measures may be addressed through structural design and emergency management plans, and this requires specific planning.

The preparation of an emergency management plan to reduce risk of loss of life could include monitoring and evacuation planning for tropical cyclones and tsunami, along with appropriate signage or distribution of safety information. This could include allowances for risks associated with winds, inundation, waves and tsunami.

Further studies

Following GEMS (2006), a major recommendation is to identify infrastructure potentially affected by storm surge and assess its capacity to withstand wave-runup stresses.

Further useful studies may include:
1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique);
2. Identification of sediment sources, sinks and key transport pathways with a focus on the supply of sediment from the south and any seasonal variability; and
3. Determination of groundwater levels in the vicinity of the chalets.

6.5.2. Quobba Station

Quobba Station (or Quobba Homestead) tourist node is located north of Point Quobba, 65km northwest of Carnarvon (Figure 1-1; Figure 6-1). It is in the secondary compartment of Point Quobba to Cape Cuvier and in the focal secondary sediment cell from Quobba Station South to Quobba Station North (Cell 10).
Comparison of historic aerial imagery is shown in Figure 6-26; Oblique aerial photos in Figure 6-27; Landforms and vulnerability in Figure G-10; Landform instability in Table G-17; Cell description in Table G-18; Susceptibility, instability and vulnerability rankings are in Table G-19 and Table G-20, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

Figure 6-26 : Aerial Photography Quobba Station (1964 and 1999)

Figure 6-27: Quobba Station Obliques 16 May 2011 and Site Photo 12 May 2011
South to North from Top to Bottom
Source: WACoast (Gozzard 2012) and Ian Eliot

Coastal susceptibility, instability and vulnerability

The secondary cell containing Quobba Station has moderate susceptibility and moderate instability, giving moderate vulnerability. Constraints to coastal management or development are moderate, including risk of inundation and wave runup, beach erosion up to the partially buried bluff in the supratidal platform and potential long-term retreat of the foredune ridge.

Advice

Construction or development on the foredunes will require significant management measures or design considerations to minimise risks of dune destabilisation, inundation and wave runup during extreme tropical cyclones or tsunami.

For any proposed development, it is recommended that a coastal hazard and risk assessment be conducted, which considers the underlying rock structure and sediment supply to the foredunes. Risk of structural damage may be reduced through structural design, including design of foundations to withstand erosion, or primary elements to sustain loads from inundation by tsunami or extreme tropical cyclonic surge and runup. Simple preliminary calculations could be conducted to estimate the risk of storm surge inundation to determine if further investigations are required.

Further studies

Any permanent tourist accommodation and development at Quobba Station requires application of SPP No. 2.6 State Coastal Planning Policy (WAPC 2003). If the risk is deemed significant using preliminary estimates, a storm surge inundation assessment may be required for a Category 5 tropical cyclone on a worst track alignment as per Schedule F.4 of SPP No. 2.6 (WAPC 2003).

6.6. GNARALOO AREA

Four Areas of Planning Interest are located in the Gnaraloo area: Red Bluff (Section 6.6.1), Three Mile Camp (Section 6.6.2), Gnaraloo Station (Section 6.6.3) and Gnaraloo Bay (Section 6.6.4).

6.6.1. Red Bluff

Red Bluff is a minor tourist node located on Quobba Station, 100km northwest of Carnarvon (Figure 1-1; Figure 6-1). It is located in the secondary compartment of Cape Cuvier to Gnaraloo Bay and at the southern end of the sediment cell from Red Bluff to Gnaraloo South (Cell 11).

Comparison of historic aerial imagery is shown in Figure 6-28 and Figure 6-29; Oblique aerial photos in Figure 6-30; Landforms and vulnerability in Figure G-12; Landform instability in Table G-21; Cell description in Table G-22; Susceptibility, instability and vulnerability rankings are in Table G-23 and Table G-24, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

Figure 6-28 : Aerial Photography Red Bluff (1964 and 1999)

Figure 6-29 : Aerial Photography Red Bluff Finer Spatial Scale (1964 and 1999)

Figure 6-30: Red Bluff Obliques 16 May 2011
South to North from Top to Bottom
Source: WACoast (Gozzard 2012)

Coastal susceptibility, instability and vulnerability

The cell containing Red Bluff has low susceptibility and moderate instability, giving low-to-moderate vulnerability. Constraints to coastal management and development are low with risks of inundation and wave runup, flash flooding, retreat of the beachface to the partially buried supratidal platform, foredune erosion and potential for altered sediment supply.

The existing Outline Development Plan assumes the foredune is a permanent feature, including recent increases of foredune width in the southern area (Figure 6-29). Foredunes are a temporary storage of sediment, dependent on sediment supply and environmental forcing and have the potential to grow rapidly or to be flattened during a single inundation event, such as a tropical cyclone. Erosion or accretion of the foredune is typically an ephemeral response to reduced or enhanced sediment supply, resulting from fluctuations of environmental conditions. The recent growth of the foredunes may partially be attributed to a lack of recent significant tropical cyclones.

There is a potential significant shift in the sediment supply to the coast and the behaviour of the beach and foredunes with projected sea level rise. One shift could be in relation to relative sea level increasing in relation to the elevation of the rock platform, altering the activity and interaction of metocean forcing with the foredunes and colluvial apron (termed sediment sheet by Ferart Design). Sea level rise, potentially exacerbated by tropical cyclone activity, could erode the beach back to the partially buried supratidal rock platform. Over the shorter term, foredune movements due to environmental variability may affect facilities at Red Bluff. Enhanced dust transport through the site is an impact associated with foredune accretion. Additional sediment would be provided to the dunefield at the northern area of the site, possibly smothering the main road into the site.

The greatest threat to human activities at Red Bluff is caused by inadequate design for infrastructure in areas susceptible to erosion, inundation and wave runup. Without consideration of emergency management, there is risk to human life and well-being during extreme storm events. Under the existing Outline Development Plan, there is likely to be ongoing costs for management, relocation and replacement of temporary coastal infrastructure. There is risk of lowering and erosion of foredunes during storm inundation events, with the risk of effluent dispersal if toilet facilities are impacted.

There is a risk of destabilisation and flow loads impacting on infrastructure placed in stream-lines off the escarpment. These are acknowledged to flow in extreme rainfall events, such as a thunderstorm or tropical cyclone, but have not been incorporated as a constraint in the masterplan. The valley village is planned in an area potentially affected by runoff.

Advice

Further consideration of coastal risk is required at the site, with clear definition of the level of acceptable risk, for all permanent and temporary infrastructure. Temporary infrastructure may be impractical at Carnarvon, as cyclone forecasting more than 1-2 days ahead contains a very large area of uncertainty, and therefore is likely to cause many false alarms, with implications for the cost of managing the facilities. The approach of using temporary or transportable infrastructure is more practical for accommodating sea level rise, accepting storm surge risk.

An emergency management plan is required for areas with a high risk of experiencing inundation, such as camping shelters, including monitoring, warning systems and the definition and dissemination of an evacuation plan.

A setback assessment should account for potential changes to the coastal environment. It is recommended at minimum to consider the risks associated with inundation and wave loading, in the context of potential foredune retreat associated with the passage of an extreme tropical cyclone. This is of particular relevance to the southern area of the site due to the coastal aspect.

The site requires further consideration and engineering advice on structural loads for infrastructure sited in terrestrial runoff pathways; and structural design for extreme wind loads.

Further Studies

A hazard and risk assessment should be conducted for the development, defining acceptable levels of risk for all temporary and permanent infrastructure. Two coastal process studies that would benefit the assessment are: (1) a storm inundation and wave runup study for present and anticipated future sea levels; and (2) a risk assessment related to sediment budget considering potential changes to sources, sinks, sediment availability and pathways under extreme events, seasonal, inter-annual and projected sea level rise timescales, identifying potential impact on the foredunes. This should consider that the site is at the southern end of a sediment cell and tertiary compartment and incorporate potential impacts of changing sea levels in relation to the supra-tidal platforms.

Engineering design of the proposed shop should include loads associated with inundation, wind and wave forcing, in the context of storm and longer-term foredune response. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) will likely be required.

6.6.2. Three Mile Camp

Three Mile Camp is a minor tourist node located on Gnaraloo Station, 120km north of Carnarvon (Figure 1-1; Figure 6-1). It is within the secondary compartment of Cape Cuvier to Gnaraloo Bay and in the central section of the sediment cell from Gnaraloo South to Gnaraloo North (Cell 12).

Comparison of historic aerial imagery for Three Mile Camp is shown in Figure 6-31; Oblique aerial photos in Figure 6-32; Landforms and vulnerability in Figure G-12; Landform instability in Table G-21; Cell description in Table G-22; Susceptibility, instability and vulnerability rankings are in Table G-23 and Table G-24, with classifications contained in Table 2-6, Table 2-11 and Figure 2-14.

Coastal susceptibility, instability and vulnerability

The cell has moderate susceptibility and moderate instability, giving a moderate vulnerability. Constraints to coastal management are moderate, including risk of cliff instability or collapse, and increased inundation or overtopping of the cliffs due to projected sea level rise.

Figure 6-31 : Aerial Photography Three Mile Camp (1963 and 1999)
The 1963 image is distorted or warped

Figure 6-32: Three Mile Camp Obliques 16 May 2011
South to North from Top to Bottom
Source: WACoast (Gozzard 2012)

The coastal cliffs near Three Mile Camp are presently subject to overtopping, with projected sea level rise likely to increase the incidence of such events, increasing the risk of loss of life particularly through king waves in an area of recreation, camping and caravanning (Figure 6-32; Figure 6-33). Camping is presently occurring within 30 m of the top of the cliff. In addition, increased wave overtopping will result in erosion and increased retreat of the calcarenite plains landward of the cliffs and supratidal bluffs. The risk of inundation during a tropical cyclone event also increases with projected sea level rise.

Cliff instability may result in partial cliff collapse (Figure 6-32), increasing the risk of loss of human life.

A potential increase in sediment supply due to projected sea level rise provides a low constraint for coastal management. The site is located in a receded barrier, with an exposed calcarenite plain (Figure G-12). With higher sea levels more sediment would be mobilised from adjacent coasts and transported onshore south of the camping area on the supra-tidal bluff.

The gap in the reef at Three Mile Campe locally increases susceptibility to bathymetric focusing of tsunami.

Rainfall runoff through access tracks decreases the stability of the sediments perched above the supra-tidal bluffs (Figure 6-32). However, the quantity of rainfall over relatively flat ground suggests this is unlikely to be a significant risk.

There is a mild risk of reduced amenity at the site for recreational use due to beach narrowing as a result of projected sea level rise. Any construction on the foredunes north of the camping area is at risk of inundation, breaching and retreat of the foredunes due to a tropical cyclone event (Figure 6-33).

Figure 6-33: Three Mile Camp Site Photos 11 May 2011
(A) Northeast view over the site; (B) Beach and foredunes north of the site; (C) Caravans within approximately 50m of the top of the bluff (30m in parts)
Source: Ian Eliot

Advice

Conduct a hazard and risk assessment incorporating the underlying rock structure, the stability of the bluffs and cliffs with risk of collapse, and the potential for overtopping during extreme events with projected sea level rise. The most significant risks are likely to be associated with potential injury or loss of human life. Risk mitigations often applied to areas subject to wave overtopping include provision of warning signs, permanently anchored emergency lines and rescue rings. However, any provision of these facilities must consider the relative level of use and potential maintenance requirements.

The location of beach access should be investigated; ensuring access is aligned away from the prevailing wind direction to resist formation of sand drift pathways. It is advised that beach access within the foredunes to the north of the camping area be minimised, as this provides a focal location for inundation and breaching of the foredunes (Figure 6-32).

Further studies

Two further studies would inform the coastal risk and hazard assessment, along with the development of an adaptation plan for retreat. The first is an assessment of cliff stability. The second is a storm surge inundation assessment for a Category 5 tropical cyclone on a worst track alignment as per Schedule F.4 of SPP No. 2.6 (WAPC 2003) for present and projected future mean sea levels. This study could focus on the potential overtopping rates and translating this to a landward setback from the supra-tidal bluff to determine the risk of human injury or loss. The allowance for sea level rise could be accounted for by raising the water level by 0.9m in the overtopping calculation.

The horizontal landward distance could be calculated as the location where the overtopping discharge is equal to a tolerable discharge for human safety. For example, the tolerable mean discharge of q=0.03 L/s/m could be selected from Table VI-5-6 in Burcharth and Hughes (2006) to allow for pedestrians to be wet from overtopping spray, yet not dangerous. Estimation of the overtopping rates at the crest of a cliff/bluff could follow the approach in Pullen *et al.* (2007), following determination of the wave height, period and water level conditions for the design tropical cyclone. Projected shifts in mean sea level could be accounted for by increasing the input water levels, which will also affect the wave conditions at the toe of the cliff. The overtopping rate at the crest could then be translated to a landward distance where discharge is reduced to the tolerable mean discharge, accounting for friction and topography. The final landward distance could translate to a setback for any infrastructure based on overtopping alone, neglecting any potential inundation. This distance would require revision in the event of partial cliff collapse and changing mean sea levels.

6.6.3. Gnaraloo Station

Gnaraloo Station, or Gnaraloo Homestead, tourist node is located in the secondary compartment of Cape Cuvier to Gnaraloo Bay and at the northern end of the sediment cell from Gnaraloo South to Gnaraloo North (Cell 12; Figure 1-1; Figure 6-1).

Comparison of historic aerial imagery for Gnaraloo Station is shown in Figure 6-34 and Figure 6-35; Oblique aerial photos in Figure 6-36; Landforms and vulnerability in Figure G-12; Landform instability in Table G-21; Cell description in Table G-22; Susceptibility, instability and vulnerability rankings are in Table G-23 and Table G-24, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

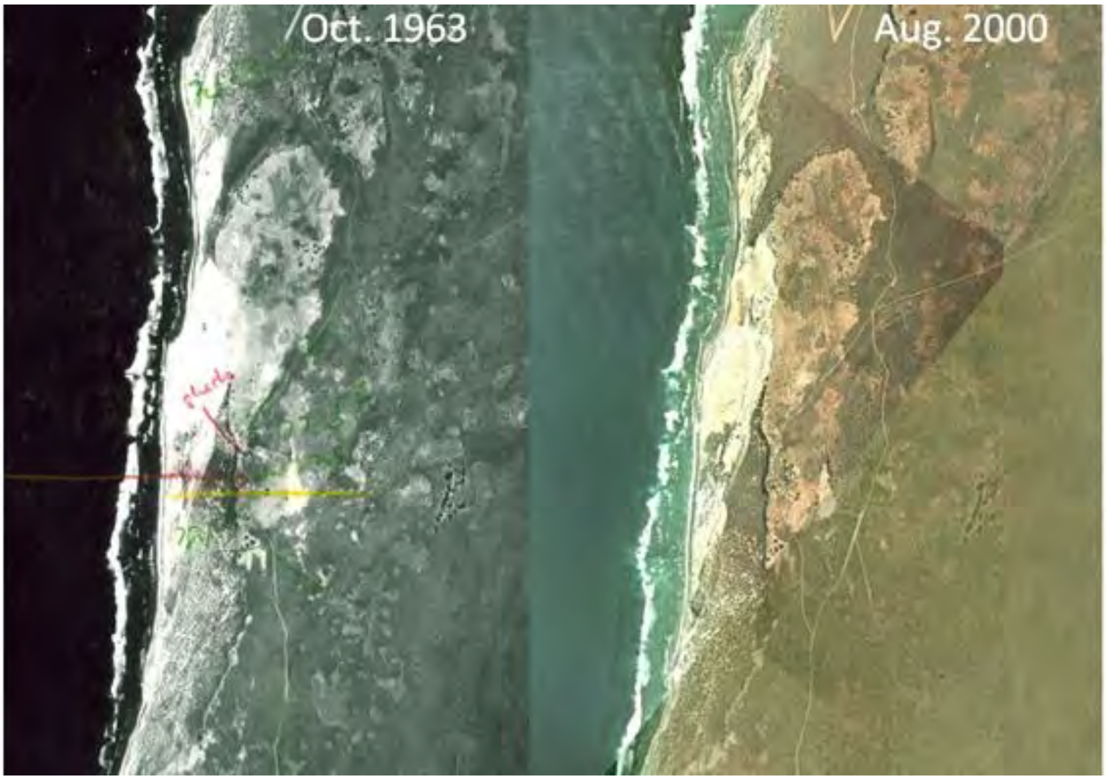

Figure 6-34 : Aerial Photography Gnaraloo Station (1963 and 2000)

Coastal susceptibility, instability and vulnerability

The cell has moderate susceptibility and moderate instability. There is a moderate vulnerability with coastal risk of dune reactivation, dune migration towards the homestead area and increased dust transport within the site possibly presenting a moderate constraint for management.

Gnaraloo Homestead is located adjacent to a perched, episodic transgressive dune system that is supplied by sediment from further south in the cell. There is a risk of dune reactivation with the dunes potentially encroaching on the site. At present the larger dune to the north of the homestead has climbed onto the calcarenite ridge (Figure 6-34; Figure 6-35; Figure 6-36), with transport accelerating once on the ridge due to exposure to higher wind speeds (Figure 6-35). Dune activity in this area increases the likelihood of transport of dust through the site. There has also been increased activity of the dunes to the south that may have the potential to smother any development further north of the present infrastructure.

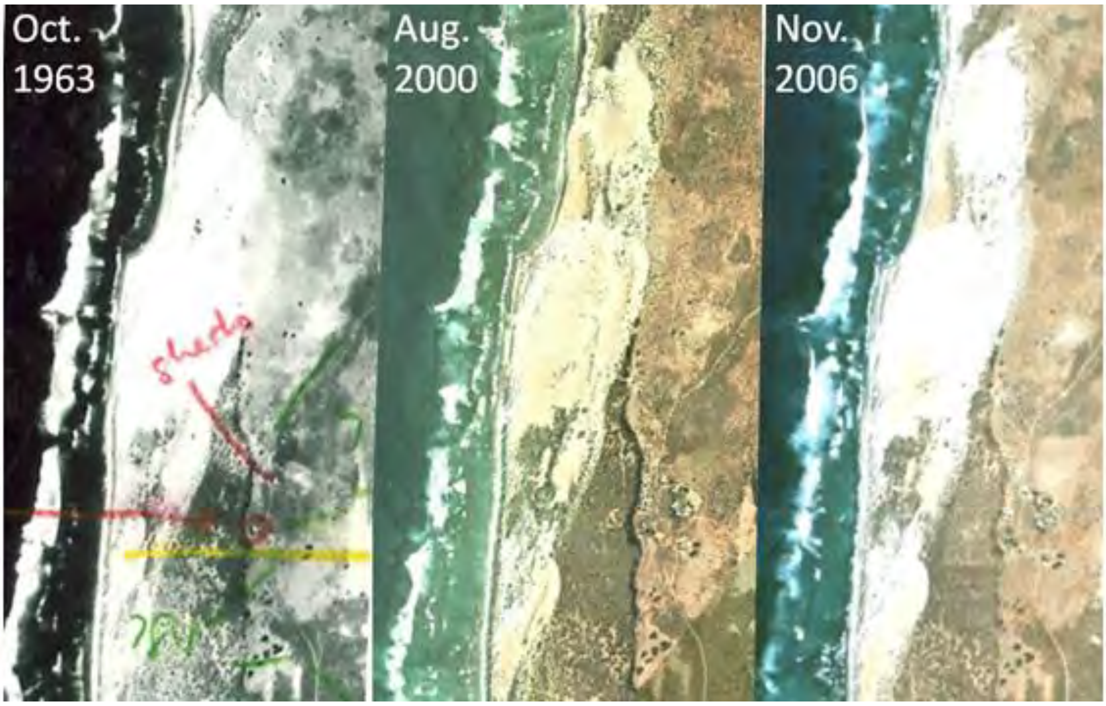

Figure 6-35 : Climbing dunes at Gnaraloo Station
2006 Image from Google Earth

Figure 6-36: Gnaraloo Station Obliques 16 May 2011 and Site Photo 12 May 2011 South to North from Top to Bottom. Source: WACoast (Gozzard 2012) and Ian Eliot

Dune activity may be affected by changes in wind direction and potential changes in rates of sediment supply to the foredunes with projected sea level rise. Sediment supply is likely to increase with projected sea level rise causing sediment mobilisation to the south of the site, with increased sediment deposited above the inter-tidal and supra-tidal platforms.

The greatest risk to present infrastructure is the potential increase in dust transport, with possible eventual smothering, of the utilities located in the hind-dune flat, seaward of the present homestead.

Advice

Conduct a hazard and risk assessment incorporating the underlying rock structure and sediment supply to the foredunes and mobility of sediments within the dunes. This information could be used to determine an accepted level of risk of dust transport and/or dune migration. An adaptation plan may be required for areas vulnerable to the impacts of dune migration, such as the hind-dune flat.

Beach access should be aligned away from the prevailing wind direction to minimise further foredune destabilisation; and the construction of a car park should allow for potential transport of dust and sand.

Further studies

The coastal hazard and risk assessment could consider the following studies to define a sediment budget and risk of dune migration:

1. Geotechnical investigations of inter-tidal and supra-tidal rock to determine potential likelihood of foredune growth;
2. Resolution of key metocean processes, particularly wind climates and variability in relation to the potential for eolian sediment transport and dune migration; and
3. Identification of sediment sources, sinks and key transport pathways with a focus on the foredune behaviour. This should consider the potential changes in supply with projected sea level rise and the interactions with the inter-tidal and supra-tidal rock.

6.6.4. Gnaraloo Bay

Gnaraloo Bay is located on Gnaraloo Station, approximately 10km north of Gnaraloo Homestead (Figure 1-1; Figure 6-1). It is presently used as a day use and boat launching site with informal camping. Gnaraloo Bay boat launch day use site is located at the southern end of the secondary compartment of Gnaraloo Bay to Alison Point and in the sediment cell from Gnaraloo Bay South to Gnaraloo Bay North (Cell 14).

Comparison of historic aerial imagery is shown inFigure **6-37**; Oblique aerial photos in Figure 6-38; Landforms and vulnerability in Figure G-12; Landform instability in Table G-21; Cell description in Table G-22; Susceptibility, instability and vulnerability rankings are in Table G-23 and Table G-24, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

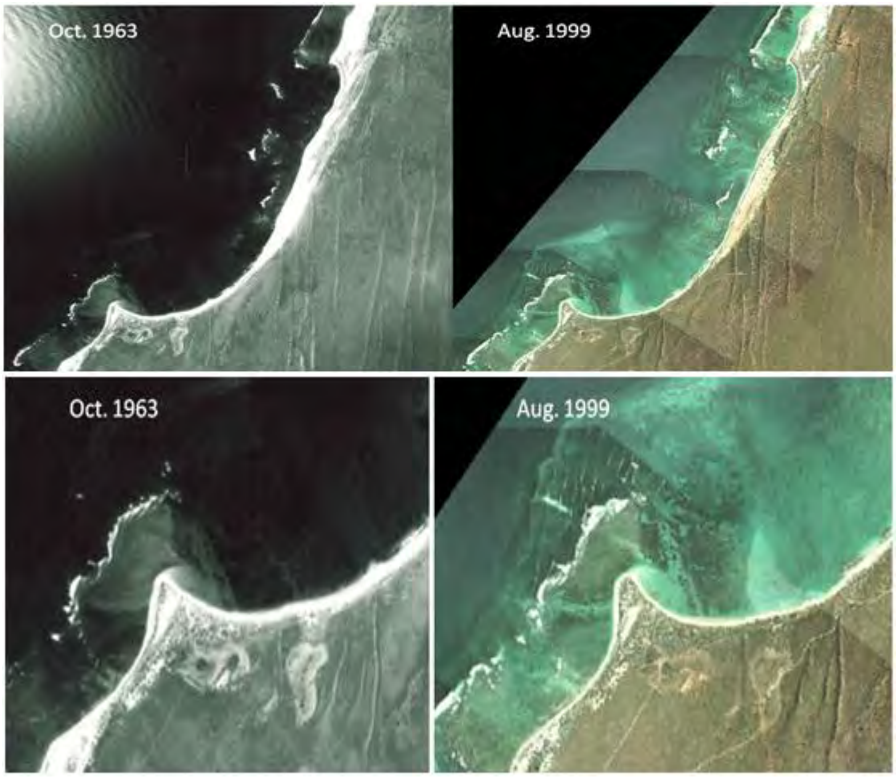

Figure 6-37 : Aerial Photography Gnaraloo Bay (1963 and 1999)

Figure 6-38: Gnaraloo Bay Obliques 16 May 2011
South to North from Top to Bottom
Source: WACoast (Gozzard 2012)

Coastal susceptibility, instability and vulnerability

The cell containing Gnaraloo Bay has moderate susceptibility and moderate instability; and has a zeta form shoreline located behind a gap in the reef system. There is a moderate vulnerability with risks including inundation in the area of the proposed ecolodge, fluctuations in sediment supply from the south and from adjacent reefs and seagrass beds, salient migration, foredune retreat and fluctuations in beach width possibly presenting a moderate constraint for coastal management.

Construction on the foredunes is likely to require management and identification of an accepted level of risk.

Construction at the proposed ecolodge location will require significant management measures and investigations. The site comprises low lying foredunes seaward of a depression that was an historic lagoon. The lagoon is located on an emergent reef platform, between cemented remnant shorelines. It is likely that the seaward extension of the lagoon contains finer sediments that may be entrained more easily, as suggested by the sediment patch on the more recent aerial photography (Figure 6-37). This location has foredunes of a lower elevation that are more susceptible to inundation and breaching, than the adjacent foredunes (Figure 6-38). There is locally enhanced risk of subsidence and higher groundwater levels due to the presence of the lagoon.

Dunes to the west of the tourism investigation envelope have patchy vegetation coverage, suggesting that there is a risk of increased dune mobility if they are disturbed, or coastal access is inappropriately managed. This could result in dust transport and potential smothering of infrastructure if placed in close proximity to the dunes.

There is a risk of sediment budget variability within Gnaraloo Baythrough modification to sediment sources, sinks and transport pathways, in the context of the geological control. The reef structure, emergent reef platform and cemented remnant shorelines that extend into the bay have implications for the rates of sediment supply and transport. Natural variability and projected change in sea level could alter the wave climate and local currents at the site. Changes in sediment supply and metocean forcing could result in salient migration, foredune retreat, rapidly fluctuating beach widths and realignment of the beach.

A rapid increase in sediment supply could promote the formation of a loosely compacted beach, which in the absence of sufficient high energy events to rework the sediment, generates a risk of boggy conditions for driving and boat launching (Figure 6-39) decreasing the amenity value of the site.

Any potential interruption of the sediment transport pathways along the coast, including dredging or construction of a boat ramp, will have impacts on the adjacent coast.

Figure 6-39: Loosely Compacted Sediments at Gnaraloo Bay 12 May 2011 (Source: Ian Eliot)

Advice

A setback assessment would be appropriate for the ecolodge area. This should account for potential changes to the coastal processes and sediment budget under extreme events, seasonal and inter-annual variations of environmental conditions and projected sea level rise. This would include an assessment of inundation and wave loading, in the context of potential foredune retreat associated with the passage of an extreme tropical cyclone; and geotechnical investigations of rock and the stability of the lagoonal sediments underlying the tourism focus area.

An emergency management plan would be useful for the ecolodge area including monitoring and evacuation planning, as the area may be at risk of experiencing inundation from tropical cyclones or tsunami.

Significant management measures would be required if any proposed works interrupt sediment transport pathways along the coast.

Further studies

The coastal hazard and risk assessment could consider the following studies to define a sediment budget and risk of foredune destabilisation:

1. Geotechnical investigations along with investigations of the geotechnical stability of the lagoonal sediments under the proposed ecolodge node;
2. Resolution of key metocean and coastal processes including variability;
3. Storm surge inundation assessment for a Category 5 tropical cyclone on a worst track alignment as per Schedule F.4 of SPP No. 2.6 (WAPC 2003) for present and projected future mean sea level. This would be recommended for the area of the proposed ecolodge, incorporating estimates of potential foredune inundation and breaching; and
4. Identification of sediment sources, sinks and key transport pathways with a focus on the potential variability in sediment supply at the site and the response of the beach, foredune and salient. This should consider the potential changes in supply with projected sea level rise and the interactions with the geological framework.

This information could be used in the application of a setback for physical processes and storm surge, incorporating the potential for foredune breaching.

6.7. CORAL BAY

Coral Bay is a tourism-focused settlement located on the Ningaloo Coast in the Shire of Carnarvon, approximately 200 km north of Carnarvon and 150 km south of Exmouth (Figure 1-1; Figure 6-1). Coral Bay settlement is located in the secondary compartment of Alison Point to Point Maud, at the boundary of two sediment cells. The boating facility at Monck Head is located in the sediment cell from Point Anderson to Purdy Point (Cell 15), with the majority of the settlement contained within the sediment cell from Purdy Point to Point Maud (Cell 16). No further discussion is included on the boating facility; however, the management of sediment bypassing could influence the Coral Bay Settlement (Damara WA 2006a). The plans for bypassing should minimise the impact on the settlement.

Comparison of historic aerial imagery is shown in Figure 6-40; Oblique aerial photos in Figure 6-41; Landforms and vulnerability in Figure G-14; Landform instability in Table G-25; Cell description in Table G-26; Susceptibility, instability and vulnerability rankings are in Table G-27 and Table G-28, with classifications in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

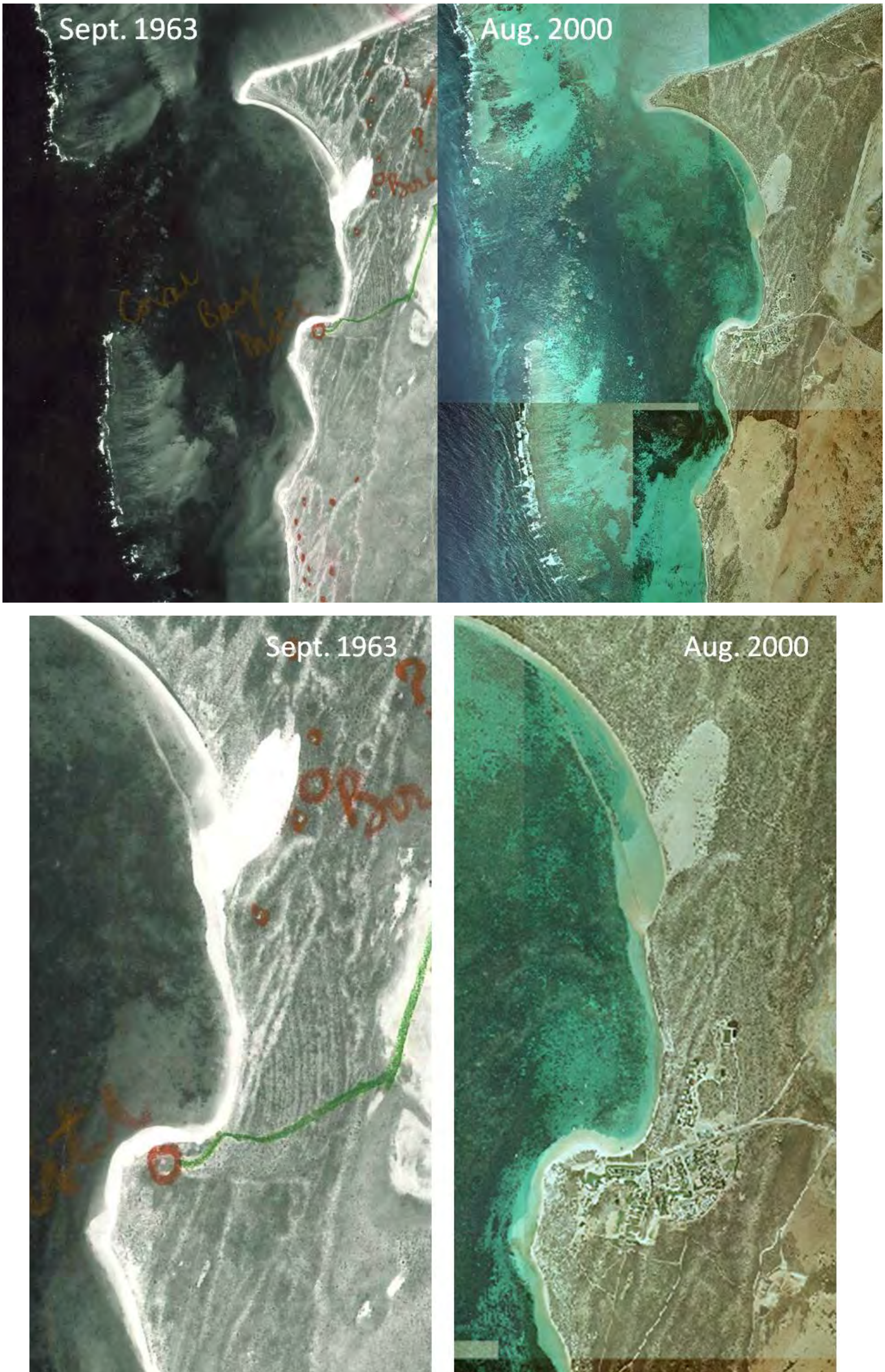

Figure 6-40 : Aerial Photography Coral Bay (1963 and 2000)

Figure 6-41: Coral Bay Obliques 16 May 2011
South to North from Top Left to Bottom Right
Source: WACoast (Gozzard 2012)

Coastal susceptibility, instability and vulnerability

The cell containing Coral Bay has moderate susceptibility and low instability. Across the cell, there is a low-to-moderate vulnerability with risks including inundation, interruption of sediment supply on the terrace and retreat of the perched foredunes in eastern Bills Bay presenting a low set of constraints to coastal management. However, when considered at a local scale, there are low-lying landforms that are subject to inundation; with potential foredune retreat presenting a greater coastal planning constraint.

Low-lying parts of Coral Bay are at inundation risk from the passage of tropical cyclones and under exceptional circumstances, from tsunami. A tropical cyclone can also cause wind damage, wave impact, beach retreat and wave runup. Areas susceptible to inundation by peak steady water level of the passage of a 'design storm' Category 5 tropical cyclone coincident with (A) high water spring tide and (B) the case of a 0.38m higher sea level are demonstrated (GEMS 2005b). Wave runup is an additional risk to loss of human life and structural damage and must be accounted for through the provision of engineering defences and emergency management where it is not included in development setbacks.

Extreme events or sea level rise with the corresponding change in inshore wave climate have the potential to cause erosion of the foredunes perched on shallow pavement on the northern part of the townsite (most unstable beachface morphology Table 2-6). The foredune stability is also related to the supply of sediment and local production of sediment on the coral reefs. A lack of sediment bypassing of the Monck Head boating facility constructed in 2007 could enhance retreat of these foredunes (Damara WA 2006a). Some historic variability in beach widths and dune activity is demonstrated in Figure 6-40, with the scarped dunes shown in Figure 6-42. There is a risk of an insufficient foreshore reserve width to accommodate landwards migration of the foredune.

Advice

An emergency management plan is required for areas with a high risk of experiencing inundation or runup, including monitoring and evacuation planning (following the recommendations for the Blowholes in Section 6.5.1).

Risk management for coastal hazards requires adaptation and risk mitigation over the full planning time frame. Development on land subject to inundation should consider risk of direct inundation, wave action, wave pressures, scour, salt water damage, run-off induced channel formation, flooding of swales and frontal dune deflation (GEMS 2005b). Some of these measures may be addressed through structural design and emergency management plans. The use of engineering defences may also provide an alternative pathway for adaptation.

Works that could interrupt sediment transport along the terrace or beachface will require consideration for the impacts on the adjacent coast with associated management measures.

Figure 6-42: Dunes Perched on Shallow Platform - Eastern Coral Bay
Source: WACoast (Gozzard 2012) 16 May 2011

Further studies

The main recommended study is to define a strategy for the protection of residents and areas of the townsite susceptible to wave runup and overwash. Risk mitigation may include special design criteria for infrastructure, engineering defences, drainage structures and preparation of an emergency management plan. Infrastructure design criteria for inundation and wave run-up may be derived using the methods outlined by GEMS (2005b; 2006).

A second recommended study is to consider the frontal dune stability for eastern Bills Bay, which could be used in a setback assessment. This may include:

1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) for the rock under the dunes; and
2. Identification of sediment sources, sinks and key transport pathways with a focus on the supply of sediment, any seasonal variability, potential retreat during extreme events and potential modifications to the sediment supply and rate of retreat with projected sea level rise.

6.8. VLAMINGH HEAD

Vlamingh Head tourist node is located 20km northwest of Exmouth adjacent to the North West Cape (Figure 1-1; Figure 6-1). It is located in the secondary compartment of Winderabandi Point to North West Cape and is located on the boundary of the two secondary cells considered in this study from Babjarrimannos to Vlamingh Head (Cell 17) and Vlamingh Head to East Vlamingh (Cell 18). The focal area for this study is Cell 18.

Comparison of historic aerial imagery is shown in Figure 6-43 and Figure 6-44; Oblique aerial photos in Figure 6-45; Landforms and vulnerability in Figure G-16; Landform instability in Table G-29; Cell description in Table G-30; Susceptibility, instability and vulnerability rankings are in Table G-31 and Table G-32, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

Figure 6-43 : Aerial Photography Vlamingh Head (1963 and 2000)

Coastal susceptibility, instability and vulnerability

The cell has low susceptibility and low instability. Across the cell, there is a low vulnerability with coastal risk of inundation and flooding unlikely to be a constraint to coastal management. However, there are certain low-lying landforms that are more likely to present a coastal planning constraint due to inundation and flooding, with risk of loss of life or injury.

Figure 6-44 : Aerial Photography Vlamingh Head Finer Spatial Scale

Figure 6-45: Vlamingh Head Obliques 16 May 2011
West to East from Top to Bottom
Source: WACoast (Gozzard 2012)

Figure 6-46: Vlamingh Head Dune Breakout and Rock Platform 16 May 2011 (Source: WACoast (Gozzard 2012))

Figure 6-47: Vlamingh Head Dune Shape Influenced by Overwash and Inundation (Source: Ian Eliot 17 May 2011)

Ephemeral creek systems draining off Cape Range provide a risk of flooding at Vlamingh Head during high rainfall events (Section 4.4.5.4). There are three creeks that drain into the Vlamingh Head tourist area, fronted by coastal dunes that were formed by alongshore eolian transport and overwash that commonly result in deltaic deposition behind the dunes. The main creek drains through the Lighthouse Caravan Park, with a floodway and floodbasin through the tourist area, draining through a 3-4m wide breakthrough in the 5-10m high dunes (Simpson *et al.* 2007; WAPC 2009; Figure 6-46). Tropical Cyclone Vance in March 1999 resulted in flooding of parts of Lot 2 and Lot 6 (WAPC 2009). Any artificial breaches in the dunes for beach access and any drainage or floodway diversions are likely to modify flood behaviour and coastal risk.

Direct inundation or overwash of dunes is a risk for Vlamingh Head during extreme tropical cyclones or tsunami. Coastal flooding infrequently affects low lying areas with surge potentially funnelling through breaches in the dunes. There is evidence of prior overwash of the 5-10m high dunes by extreme water levels (Figure 6-47). Areas of highest risk of inundation can be derived from modelling of potential tsunami inundation conducted for the area following the observations of the June 1994 tsunami (Figure 6-48; Simpson *et al.* 2007). Focal points for inundation are the coastal car parks and through the dune breach associated with the ephemeral creek, flooding the road and caravan park.

Advice

Any future plans require a coastal hazard and risk assessment, including a definition of acceptable risk. This should identify the acceptable risk to property and loss of well being. Risk to property may require consideration of loading due to wind, coastal flooding inundation from tropical cyclones or tsunami, terrestrial flooding including accumulation in floodbasins and the geomorphic response. Such an assessment should follow AS NZS (2009) ISO 31000 processes.

The allocation of land for expansion of tourist accommodation should incorporate risk of ephemeral creek flooding, including an assessment of the stability of dune breakouts, floodbasins and impacts of human intervention on flooding. Evaluation of the potential for breakout closure, and associated higher flooding, may require consideration of the sediment budget and supply of sediment to the dunes.

An emergency management plan is required due to the high risk of tsunami and tropical cyclone inundation and terrestrial flooding at Vlamingh Head. The preparation of an emergency management plan could include monitoring and evacuation planning for tropical cyclones, tsunami and ephemeral creek flooding. Following GEMS (2009), the steps to be taken could include:

1. Development of a monitoring system that identifies:
    a. Tropical Cyclones with the potential to threaten Vlamingh Head, and the predicted coincidental tidal conditions. Information available for such an assessment is held by the Bureau of Meteorology and the Department of Transport, although this requires subsequent interpretation to identify the risk at Vlamingh Head;
    b. Tsunami with the potential to threaten Vlamingh Head. The information for this assessment could be obtained by the Australian Tsunami Warning System, coordinated by the Bureau of Meteorology, Geoscience Australia and Emergency Management Australia;
2. Installation of signage at coastal car parks and/or distribution of safety information regarding tsunami to inform the transient visitors to the area of the risk. This information is available from Emergency Management Australia;
3. Definition and dissemination of an evacuation plan, particularly for the areas that may be at greater risk of flooding or inundation.

Further studies

The following studies could be used for a hazard and risk assessment:

1. Risk of tsunami inundation incorporating the modelling by Simpson et al. (2007);
2. Risk of tropical cyclone inundation;
3. Flood study of the ephemeral creek in Vlamingh Head including floodplain basins, floodways and behaviour of the dune breakout. The impacts of any potential human intervention on flooding should be incorporated; and
4. Identification of sediment sources, sinks and key transport pathways with a focus on the dynamic capacity of the dunes, including potential dune breakouts. Consider the potential changes in sediment supply that could occur under changing metocean forcing, including behaviour of the terrace, and how the beachface and foredune plain may respond. Alongshore transport can potentially occur in both directions. The sediment budget should be placed in the context of the underlying geological framework.

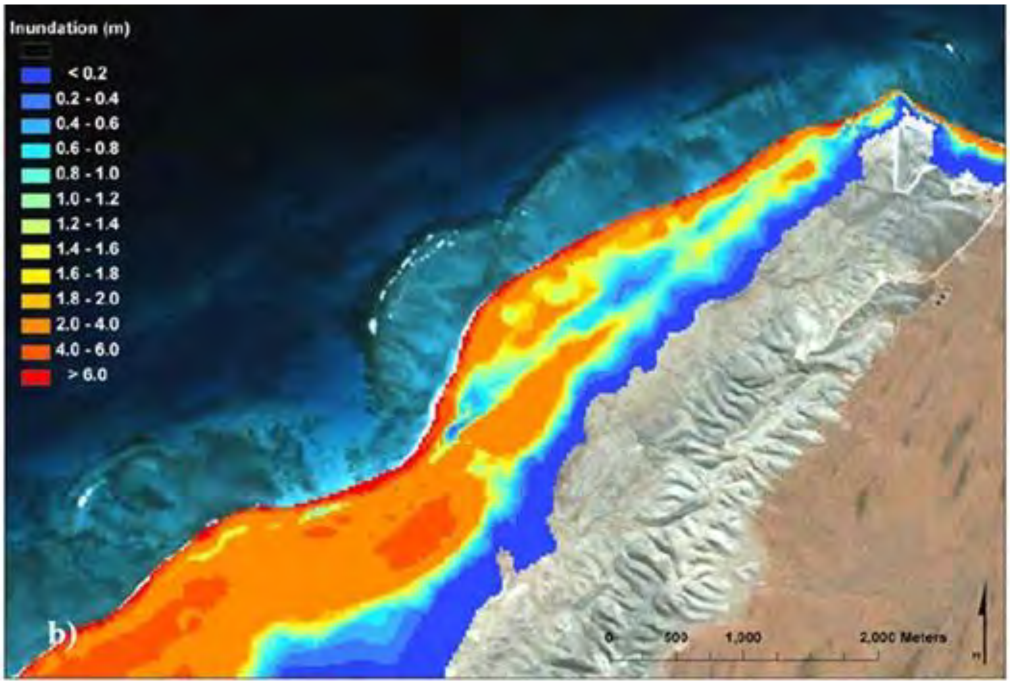

Figure 6-48: Tsunami Inundation Model for Vlamingh Head for Scenario in Figure 4-6A (Source: Simpson *et al.* 2007)

6.9. EXMOUTH

Exmouth is the main town for the Shire of Exmouth, located on the western side of Exmouth Gulf (Figure 1-1; Figure 6-1). It is located in the secondary compartment of North West Cape to Learmonth, crossing two sediment cells. The military facility is located in the sediment cell from Bundegi to Exmouth North (Cell 19), with the majority of the townsite contained within the sediment cell from Exmouth North to Qualing Pool (Cell 20).

Comparison of historic aerial imagery is shown in Figure 6-49; Oblique aerial photos in Figure 6-49; Landforms and vulnerability in Figure G-18; Landform instability in Table G-33; Cell description in Table G-34; Susceptibility, instability and vulnerability rankings are in Table

G-35 and Table G-36, with classifications contained in Table 2-6, Table 2-10, Table 2-11 and Figure 2-14.

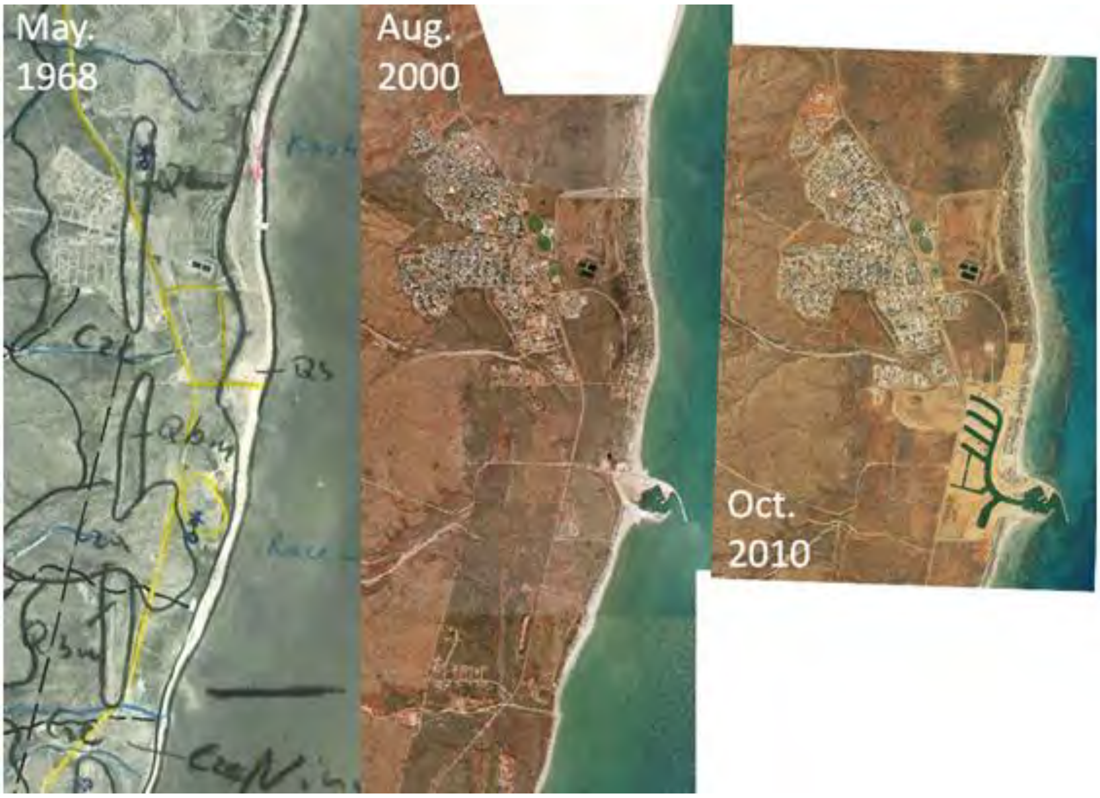

Figure 6-49 : Aerial Photography Exmouth (1968, 2000 and 2010)

Figure 6-50: Exmouth Obliques 16 May 2011 – South of Harbour
South to North from Top to Bottom
Source: WACoast (Gozzard 2012)

Figure 6-51: Exmouth Obliques 16 May 2011 – North of Harbour
South to North from Top to Bottom
Source: WACoast (Gozzard 2012)

Coastal susceptibility, instability and vulnerability

Both cells have low susceptibility, with moderate instability in the southern cell (Cell 19) and low instability in the northern cell (Cell 20). Across the whole cell containing the townsite (Cell 20), there is low coastal vulnerability, which suggests limited constraints to coastal management. However, when considered at a local scale, there are several low-lying landforms that are more likely to present a coastal planning constraint due to runoff flooding, storm surge inundation and dune stability. The combination of floodbasins of ephemeral creeks fronted by a narrow primary dune potentially provides a significant constraint for coastal management.

Ephemeral creek systems provide a risk of flooding at Exmouth during high rainfall events, demonstrated by the flooding associated with Tropical Cyclone Vance in March 1999 (Martens *et al.* 2000; SKM 2007), a Northwest cloudband in June 2002 (SKM 2007) and Tropical Cyclone Pancho in March 2008 (Section 4.4.5.4). The six catchments through the townsite flooded during the passage of TC Vance, with increased runoff due to the lack of vegetation in the catchments following a bushfire (Martens *et al.* 2000). The small coastal catchments, totalling 45 km^2, are fronted by coastal dunes that were formed by alongshore eolian transport and commonly result in deltaic deposition behind the dunes. Inundation of flood basins and dune breakouts can occur during a significant flood, with the location of breaching influenced by areas of historic breakouts, narrow dune width and human intervention. The risk of flooding could be based on the floodplain modelling by SKM (2007). However, artificial breaches in the dunes for beach access and any drainage or floodway diversions modify flood behaviour and coastal risk, which may render previous flood studies obsolete.

Dune breaches or low points also provide a pathway for coastal inundation associated with tropical cyclone surge or tsunami (Figure 6-52). These events have erosive capacity for the primary dune.

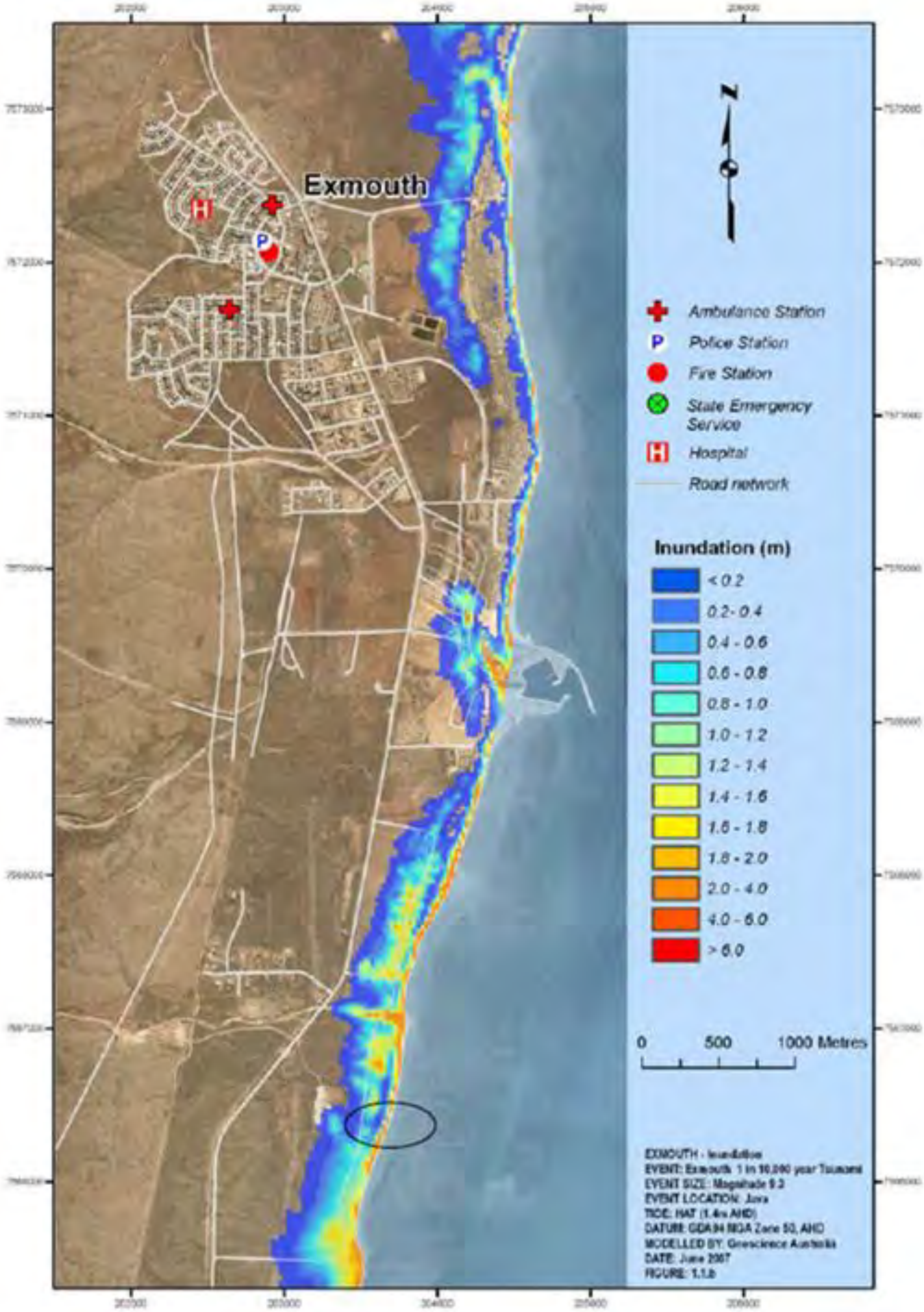

Figure 6-52: Tsunami Inundation Model for Exmouth for Scenario in Figure 4-6A
The black oval indicates access point that breaches major dunes
(Source: Simpson *et al.* 2007)

The primary dune presently provides some protection from tropical cyclone surge and inundation and direct wave attack. The dunes are supplied by eolian transport, overlying a rock pavement foundation. There is alongshore transport on the terrace, beachface and into the dunes that can potentially occur in both directions, but has demonstrated sustained nett northwards transport since the installation of the harbour breakwaters. If there was a significant modification to sediment supply, including an absence of sand bypassing, the risk of dune breaching may increase. In addition, artificial breaching for beach access and diversion of drainage floods could potentially change the flood basin behaviour landward of the dunes.

Any breaches in the dune may widen rapidly, increasing the risk of inundation of the land behind. Dune breaches can also rapidly infill, temporarily acting as a sediment sink and altering the sediment supply of the adjacent coasts. Dune stability is affected by the number, width and locations of breakouts; along with the sediment supply and the potential for further breakouts based on terrestrial and coastal flooding.

Advice

An emergency management plan is required for areas with a high risk of experiencing inundation, including monitoring and evacuation planning.

Risk management and adaptation to mitigate coastal hazards requires planning for reduction of the risks over the full planning time frame. This is especially so in consideration of decisions about coastal land subject to potential inundation and flooding associated with extreme events such as the passage of a tropical cyclone or a tsunami. Any future plans may consider preparation of a coastal hazard and risk assessment, including a definition of acceptable risk. This should include the acceptable risk to property and loss of well being. Risk to property may require consideration of loading due to wind, coastal flooding inundation from tropical cyclones or tsunami, terrestrial flooding including accumulation in floodbasins and the geomorphic response. Such an assessment should follow AS NZS (2009) ISO 31000 processes. An acceptable level of risk may be met through structural design and emergency management plans, and this particularly requires planning.

The risk of ephemeral creek flooding should also include an assessment of the behaviour of dune breakouts, floodbasins and impacts of human intervention on flooding. Examples of intervention include the placement of bunds to divert flood flows, artificial breaching of the dunes and infilling of the flood basin. This may require consideration breakout dynamics, recognising the supply of sediment to the dunes.

An emergency management plan is required due to the high risk of tsunami, tropical cyclone inundation and terrestrial flooding at Exmouth. The preparation of an emergency management plan to reduce risk of loss of life and well being could include monitoring and evacuation planning for tropical cyclones, tsunami and ephemeral creek flooding. The highest risk of loss of life is associated with tsunami inundation. Following GEMS (2009), the steps to be taken could include:

1. Development of a monitoring system that identifies:
    a. Tropical Cyclones with the potential to threaten Exmouth, and the predicted coincidental tidal conditions. Information available for such an assessment is held by the Bureau of Meteorology and the Department of Transport, although this requires subsequent interpretation to identify the risk at Exmouth;
    b. Weather systems that have the potential to result in ephemeral creek flooding. Information is held by the Bureau of Meteorology;

   c. Tsunami with the potential to threaten Exmouth. The information for this assessment could be obtained by the Australian Tsunami Warning System, coordinated by the Bureau of Meteorology, Geoscience Australia and Emergency Management Australia;
2. Installation of signage at coastal car parks and within the marina and/or distribution of safety information regarding tsunami to inform the transient visitors to the area of the risk. This information is available from Emergency Management Australia;
3. Definition and dissemination of an evacuation plan, particularly for the areas that may be at greater risk of flooding or inundation.

Further studies

The following studies could be used for a hazard and risk assessment:

1. Risk of tsunami inundation incorporating the modelling by Simpson et al. (2007);
2. A tropical cyclone surge assessment under Schedule F.4 of SPP No. 2.6 (WAPC 2003) for a design cyclone following recommendations by Damara WA (2009) including wave runup;
3. Risk of flooding and flood loading including the behaviour of floodplain basins, floodways and the dune breakouts following the flood study by SKM (2007). The impacts of any potential human intervention on flooding since the SKM (2007) study and proposed as part of future plans should be incorporated; and
4. Determination of a sediment budget with a focus on the dune stability in the context of the underlying geologic framework. Dune stability assessments should investigate the number, width and locations of the breakouts; sediment supply and potential for further breakouts based on terrestrial and coastal flooding. Potential modifications to the sediment budget and dune stability with proposed works should be included.

7. Discussion & Overview

The key aim of the project was to provide strategic advice concerning the geomorphology of the Gascoyne coast between the mouth of the Murchison River near Kalbarri and Locker Point on the eastern shore of Exmouth Gulf. Particular reference is made to Areas of Planning Interest at fifteen sites: Nanga, Denham, Little Lagoon, Monkey Mia, Carnarvon, Miaboolya Beach, Quobba-Blowholes, Quobba Station, Red Bluff, Three Mile Camp, Gnaraloo Station, Gnaraloo Bay, Coral Bay, Vlamingh Head and Exmouth. Accordingly, coastal landforms for the Study Area have been examined at two scales. First strategic information is at the scale of secondary coastal compartments and involves description of the unconsolidated land systems and their relationship with the geologic framework. The framework is provided by the underlying coastal limestone and sandstone. The large scale land systems include the landform associations of river deltas, dune barriers and rocky coasts. The second scale is related to local area planning and examines landforms in discrete sediment cells identified for each Area of Planning Interest.

Two facets of coastal change were considered to provide a strategic description of the vulnerability of coastal land systems and landforms to current and projected changes in environmental forcing. First, the relative susceptibility or potential for erosion of a geologic structure in response to variation in metocean processes, particularly changes in sea level was estimated for different landform systems and landforms comprising the coastal compartments and sediment cells. Second, levels of relative instability were ascribed to landforms according to their current responses to metocean processes such as storms and sediment supply as well as anthropogenic factors. The estimates of susceptibility and instability were then combined to indicate the likely vulnerability of the land systems and landforms within the compartments or cells. Vulnerability in this context provides an overall estimate of land system and landform susceptibility and instability for each planning unit.

Combination of the susceptibility of coastal land systems to changes in the metocean regime with the present stability of landforms they support identifies components of the coast potentially subject to risk in response to projected environmental change. Both facets are applicable at each level in the planning hierarchy and have relevance to coastal land use. Coastal plans traditionally focus on the instability of coastal landforms, with allowances for erosion (coastal setbacks) related to the historical variability of the beach-foredune system under consideration as well as projected sea level change (WAPC 2003, 2006). However, feedback mechanisms linking structure and stability determined that landform susceptibility to metocean forcing is at least as significant, with changes in either susceptibility or stability highly likely to trigger changes to the other, particularly on unconsolidated coasts.

The potential contribution of vulnerability assessment based on the susceptibility and instability of land systems and landforms to a more complete risk assessment process, such as that proposed by ISO 31000 (Standards Australia 2009), is illustrated in Figure 7-1. This is discussed further in Section 7.4.1 below.

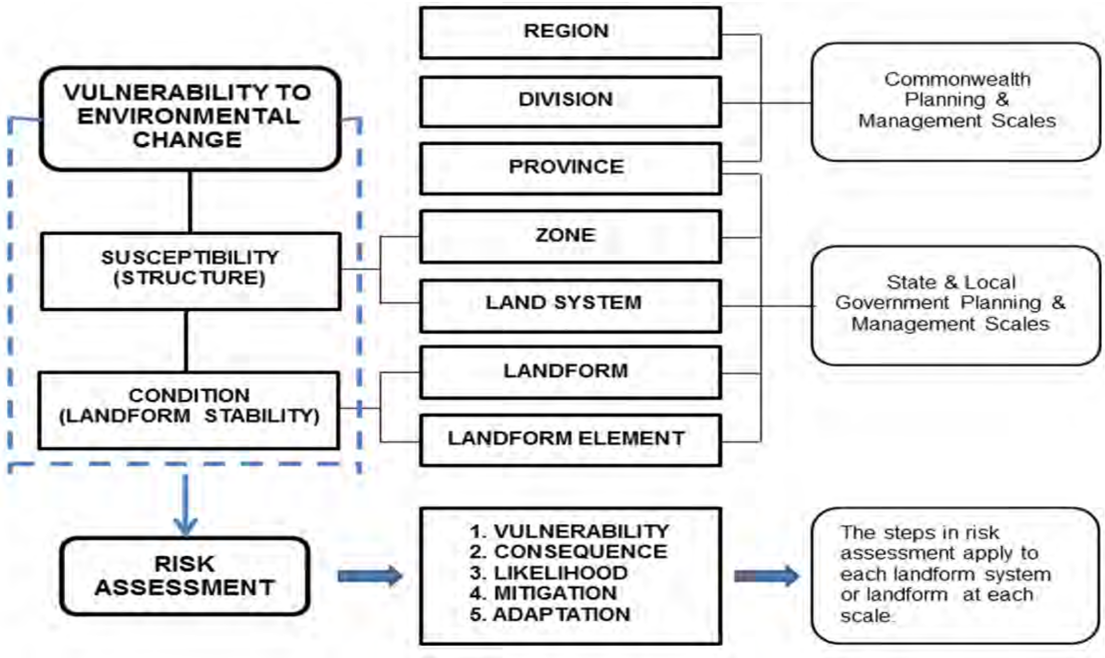

Figure 7-1: Vulnerability Assessment, Risk Assessment and Scales of Application

7.1. ASSESSMENT SCALES

At a geological timescale, the hard-rock geologic framework has provided topographic control for formation of Holocene coastal landforms and land systems developed during the past 10,000 years. Accretionary structures such as deltas and barrier dunes formed as unconsolidated sediment accumulated along the coast between the Murchison River and Locker Point. Additionally, during the late Holocene sea level changes and the metocean processes accompanying them have also re-inundated and affected the morphology of older unconsolidated landforms; particularly the Boodalia and Browne deltas of the Gascoyne River and the Wooramel delta, the low-lying outwash plains and salt flats at Wooramel and Yannarie; and the extensive sub-tidal terraces fringing the shores of Shark Bay. Albeit slowly, the coast is continuing to develop at present as sediment is moved along and across the shore. The structure of the land systems, with unconsolidated Holocene sands overlaying older limestone and sandstone topography in places, implies marked geographic variation in the susceptibility of the shore to erosion and the need to apply different models for the prediction of shoreline movement to different parts of the coast. Hence assessment of the susceptibility of the coast to observed and projected changes in metocean conditions has been undertaken for sediment cells that support different landform associations.

Land system susceptibility has been estimated on a comparative basis as being low, moderate or high depending on the presence, extent and elevation of outcropping bedrock. At the broadest scale a river delta or barrier may not be susceptible to long-term change whereas elsewhere a different type of delta or barrier system may be highly susceptible. This is apparent when the perched barriers along the coast between Nanga and Denham are compared to the extensive, complex barrier system between the Gascoyne River mouth and Bejaling Hill which may have formed over a deeper rocky basement. A similar comparison may be made between the outwash plains and tidal flats of the Wooramel and Yannarie land systems. The disparity provides rationale for more detailed consideration of the geotechnical qualities of the different systems.

The association of landforms comprising sand barriers along the coast, particularly their geographic extent provides an indication of sediment availability. For example, Roy *et al*. (1994) attributed the type of barrier found on wave dominated coast to variation in continental shelf gradient and sand supply as well as the wave regime. The types they identified ranged from (a) sediment poor areas of eroding coast where there was a continuing loss of sand onto a steep continental shelf to (b) transgressive dune barriers and a large sand supply from a low-gradient continental shelf. With notable variations their models are applicable to parts of the Gascoyne coast. Barrier types vary along the Gascoyne coast, ranging from the extensive prograded and episodic transgressive system north of the Gascoyne River, through receded barrier systems along the Gnaraloo shores, and in Shark Bay, to mainland barriers or no barriers on the exposed rocky coast between the Murchison River and Steep Point. Together with the relative stability of the coast at present, these indicate substantial geographic variation in volumes of sediment moving alongshore and shoreward and bring into question the time scales at which phases of sediment loss and accretion are occurring.

The extent and phases of dune activity through the Holocene are apparent as nested blowouts and parabolic dunes which form barrier ridges. Hence, small variations in dune activity identified from the photographic record used to examine the Areas of Planning Interest (Section 6) indicate the phases are associated with variation in the intensity and duration of metocean processes, particularly with long-term fluctuations in sea level and variation in sediment supply to the coast. Over a planning horizon of decades to 100 years, these will continue to contribute to development of the barriers through the formation and destruction of foredunes, blowout activity and the migration of nested parabolic sand dunes, especially along parts of the shore susceptible to erosion.

Rise in sea level, whether a recurrence of historically extreme conditions due to storminess or a result of projected Global warming, potentially would trigger increased destabilisation of the foredunes and frontal dune belt along the shore as well as changes to the balance between fluvial discharge and tidal creek dynamics on tidal flats of the outwash plains and deltas. It would facilitate landward migration of barriers where they not perched on bedrock surfaces well above high tide level. The broad scale assessment of vulnerability provides an indication of which areas are most likely to change whereas consideration of the Areas of Planning Interest at a local scale provide more specific detail concerning land forms at risk. Establishment of a rate of projected change requires estimation at a local scale due to the wide differences landform setting over a short distance.

At sub-decadal time scales, interaction of modern metocean processes with the inherited geologic framework has two ramifications.

1. First, alongshore variation in coastal alignment, beach erosion and deposition, foredune formation and dune development occurs as a result of this interaction. The reaches of coast most susceptible to environmental change are commonly in close proximity to shoreline salients and extensive rock outcrops.

2. Second, it invalidates application of the Bruun Rule (Bruun 1962) that has been widely applied in the calculation of setback to development on mixed sandy and rocky coast in Western Australia (WAPC 2003); a point made by Bruun himself in his criticism of the application of the 'rule' (Bruun 1983, 1988). This implies that localised estimation of shoreline change is necessary and should be linked to geophysical determination of the distribution and elevation of the underlying limestone topography supporting the barrier at places where development is under consideration.

7.2. ADVICE

A precautionary approach was adopted for the purposes of this report in the absence of an existing policy for susceptibility and instability on mixed sand and rocky coast or on the low-lying morphology of tidal flats, as occur on much of the Gascoyne coast. The approach involved an analysis of coastal vulnerability based on available information, including published descriptions of the relative susceptibility of coastal land systems to change with variation in metocean processes as well as the current stability of individual landforms comprising them. The vulnerability analysis is the first part of a more extensive risk assessment which would identify the processes of change in more detail; examine social and economic implications; determine the consequences of projected and existing patterns of coastal change; and plan and implement adaptation strategies. Some of the adaptation strategies are embedded in the guidelines of the State Coastal Planning Policy (SPP No. 2.6) and these provide the principles and rationale for the advice arising from examination of vulnerability on the Gascoyne coast.

7.2.1. General Principles

General principles applied in framing the recommendations are as follows:

1. The State Coastal Planning Policy SPP No. 2.6 identifies a range of considerations for the determination of coastal setbacks. The first two factors identified are coastal erosion and landform instability. Both are related to the interactions amongst the metocean processes, geological framework, unconsolidated sediments and landforms comprising the morphodynamic system of the coast. Briefly, following Wright & Thom (1977), a basic tenet of the vulnerability assessment applied here is that if one component of a morphodynamic system changes the rest respond to some extent on the geologically controlled Gascoyne coast.

2. The distribution and elevation of the coastal limestones and sandstones, as well as the extensive tidal flats of the coast are significant in that the presence of mud and rock invalidates the so called 'Bruun Rule' of erosion (Bruun 1962) which is commonly applied in setback calculations under the State Coastal Planning Policy SPP No. 2.6. This point was made by Bruun (1983, 1988) in his critical assessment of the 'rule'. However, the rocky topography provides a geological framework for the development of unconsolidated, sedimentary landforms and therefore is a major determinant of the susceptibility of the coast to changes in the metocean regime.

3. A secondary determinant of the susceptibility of a coastal land system is related to the volume of unconsolidated sediment comprising the landforms of the shoreface (Houser & Mathew 2011). Herein the principle followed is that the different types and

dimensions of barrier systems, river mouths and rocky topography present along the coast are related to sediment availability. Although outside the scope of this report, this proposition warrants closer consideration, particularly with respect to the perched barrier systems of the coast.

4. Conceptual models of beach type, barrier structure, dune typology and river mouth morphology developed elsewhere (Section 2.4) are broadly applicable to the Gascoyne coast and identification of the relative stability or instability of coastal landforms.

7.2.2. Coastal Management Advice

Advice specifically pertaining to the coastal planning and management of each sediment cell is listed in Appendix G, following the format outlined in Table 2-12. This format ensures a consistent interpretation has been applied for planning and management purposes, and that it complies with established guidelines promulgated by the WAPC (2003), DPI (2006) and DoT (2010).

Detailed interpretation and advice has also been made for the ten Areas of Planning Interest in Section 6 above. These follow the same format as the analysis of the cells containing them.

More specific information on the structural integrity (susceptibility to change) and stability (instability) of landforms is obtainable through combined interpretation of the landform descriptions for each cell (Appendix G) and the criteria used to rate landform susceptibility and stability (Table 2-6).

More general advice is as follows:

1. Preliminary schedules in the State Coastal Planning Policy (SPP No. 2.6) are outlined for the calculation of coastal erosion allowance, but there is no corresponding information for the susceptibility of a landform system to metocean forcing or the overall instability of landforms comprising the system. It is recommended the two aspects of coastal vulnerability be addressed in any review of the policy guidelines.
2. Locally the elevation of limestone or sandstone underlying the beach and dunes directly affects the susceptibility of the coast to changes in metocean forcing and influences coastal stability. It is a factor that could be determined as a planning requisite prior to implementation of any development proposal involving the establishment of rural-urban infrastructure in areas where there are perched barriers and beaches.
3. Policy and guidelines related to the siting of infrastructure on barrier systems is currently lacking. Different types of barrier support different assemblages of dunes. Determination of setback to development could be tailored to the different types with a larger setback allowance for stationary and eroded barriers as well as low-lying beach ridge plains that are notably susceptible to change due to metocean forcing.

4. Overall, the seaward part of most barrier systems is highly susceptible to destabilisation by metocean forcing, which also means it is highly likely to be destabilised through land use pressures.
    a. Following the guidelines of the State Coastal Planning Policy (SPP No. 2.6), it is advised that shore parallel development of infrastructure such as coast roads, car parks and buildings should not occur in the frontal dunes when there is a history of dune instability.
    b. Additionally, cells with an unstable (moderate or high instability ranking) are likely to require controlled beach access from the coastal hinterland.
5. It is advisable that a wide setback for growth and change in dune landforms be established in places where foredunes are missing or eroded, and where more than approximately 50% of the length of coast along the vegetation line on the backshore of the beach is influenced by active blowouts.
6. Parts of the Gascoyne coast are markedly affected by tropical cyclones and may be subject to river flooding and tsunami inundation. Emergency management plans, including monitoring and evacuation plans, are required for areas of high risk as indicate in Section 6.
7. Due to the high level of risk It is recommended flood risk due to terrestrial flooding and marine inundation be reviewed on a 10-year basis for reasons of:
    - Uncertainty with climate change projections (GEMS 2009);
    - Flood risk implications of surge and flood mitigation and management techniques; and
    - Flood risk implications arising from ongoing changes to the geomorphology.

7.3. INCORPORATION IN POLICY

The susceptibility of coastal land systems to projected changes in metocean forcing over a planning horizon of 100 years, and the stability of the landforms each system supports could be incorporated in existing State planning policies and guidelines (WAPC 2002, 2003; DPI 2006). Examples of susceptibility, instability and vulnerability rankings as well as their implications for planning and recommended planning guidelines are listed in Table 2-12. The rankings, their implications for land use and suggested guidelines for management are listed in Appendix F for each of the compartments and in Appendix G for cells examined in the Areas of Planning Interest.

The analysis of compartments and cells is intended to provide a natural framework with potential for a variety of applications in coastal planning and management. In this context Geographic Information Systems (GIS) models of the cells may be populated with information at the user's discretion and at appropriate spatial scales. Under the policy and guidelines provided by the State Government, possible applications depend on the information linked with cells as overlays or tables for comparative purposes as has been done in this report. Potentially, applications range from structured audits of coastal population associated with individual land systems or landforms, infrastructure, beach use and tourism activities to comparative assessment of different parts of the coast to geographically different hazards and risks.

Direction for coastal planning and management by the State and Local Government is provided in the Coastal Zone Policy for Western Australia (WAPC 2001). The policy supports strategic objectives for environmental, community, economic, infrastructure and regional development interests; particularly through the recognition of natural hazards and minimisation of risk to people and property. Application of coastal zone management is mainly directed through the *State Coastal Planning Policy* SPP No. 2.6 (WAPC 2003), the Coastal Protection Policy (DPI 2006) and *Sea Level Change in Western Australia* (DoT 2010) recommendations for inclusion of sea level change projection in coastal planning. These policies contain specific reference to incorporation of coastal landforms and metocean processes in coastal planning and management. The reference provides a direct link to the hierarchy of coastal compartments and sediment cells and, through them to coastal planning at all levels.

SPP No. 2.6 (WAPC 2003) promotes the establishment of coastal setbacks and foreshore reserves to achieve strategic objectives of the *Coastal Zone Policy* for Western Australia (WAPC 2001), with focus on the following:

- *Recognition of the dynamic nature of coastal environments and the consequences for coastal development and use.*
- *Avoidance or mitigation of the impacts of natural hazards through intelligent siting and design of infrastructure, based on ongoing scientific research.*

Through the SPP No. 2.6 (WAPC 2003) and the Coastal Protection Policy (DPI 2006) it is recognised that land developments may be adversely affected by a range of physical processes occurring at the coast, with three of the most common being:

- Coastal erosion or accretion;
- Coastal flooding; and
- Coastal landform instability.

A general method for calculating a horizontal setback allowance for coastal erosion is outlined in the SPP No. 2.6. Calculation of coastal setback to development is most appropriate at more-detailed local area planning and site scales than the sediment cell scale adopted for this report. However, the principles of recognising coastal dynamics and avoiding adverse impacts incorporated in the policy are relevant to vulnerability assessment. They are applicable in assessment of flooding and landform instability. Although site specific, they loosely entrain consideration of the susceptibility of each site to potential change and its current state of stability. Typically applications of SPP No. 2.6 include identification of minimum development levels, or minimum reserve widths to cater for shoreline movement and changes in sand dune formations.

Where use of wide setbacks is not practical or subsequent shoreline change has significantly reduced a setback allowance the Coastal Protection Policy (DPI 2006) allows for development of protective structures. However, clear justification for protective works is required, and unacceptable adverse environmental, social or financial impacts to neighbouring areas must be avoided. Within this context, the effects of sand impoundment by a protective structure must be considered:

"The natural supply of littoral sand is a resource shared by all West Australians. Accordingly, those benefiting from future works or developments that change the natural supply of sand along the coast shall compensate for the change to that supply..."

The points made in State coastal policy guidelines of the WAPC (2003), DPI (2006) and DoT (2010) provide direction for the recommendations arising from the vulnerability analysis in two respects. First, coastal development should not be proposed in areas where there is a high probability of adverse environmental and other impacts occurring that would require installation of protective works. Second, the requirement to consider the impact of proposed development on sand impoundment necessitates determination of the coastal sediment budget at a scale commensurate with the scale of the proposed development.

Through its context in coastal policy guidelines the vulnerability assessment also provides insight into approaches that may be used in land use adaptation to projected climate change and rise in sea level. Different facets of adaptation may be considered. For example, in undeveloped areas where there is a higher than moderate level of risk the vulnerability analysis can be used to plan avoidance of sites with potential risks or incorporated in plans that include contingency measures should development be necessary. Second, in areas with established infrastructure the vulnerability analysis may be used to determine the suite of environmental problems requiring more detailed risk assessment and the incorporation of social and economic considerations.

7.4. FURTHER STUDIES

In addition to further studies required for hazard and risk assessment under the State Planning Policy 2.6 (WAPC 2003) requirement for them is founded the need to redress information gaps and for management purposes.

7.4.1. Risk Assessment

This report is intended to be indicative rather than prescriptive and have application for strategic planning purposes. It focuses specifically on the current and potential changes to the geomorphologic features of the coast. In a more complete assessment of coastal hazard and risk the assessment should be extended to include descriptions of landform change associated with meteorologic and oceanographic variables as well as consideration of the social and economic factors at risk. Results reported herein thus provide a first step to the application of more detailed risk and coastal vulnerability assessment procedures, such as those described by Kay *et al.* (1996), Brooks (2003), Harvey & Nicholls (2008), Harvey & Woodroffe (2008) and Finlayson *et al.* (2009). It broadly establishes the first steps to a full risk assessment. Full risk assessments are recommended for developed areas , including the townsites, and areas subject to increasing use for tourism and recreational purposes.

Frameworks and guidelines for risk assessment previously have been applied in an assessment of risk to the sustainability of a coastal, natural-resource based industry by Ogburn & White (2009) and to coastal management in New South Wales by Rollason *et al*. (2010). Both applications use the AS/NZS ISO 31000 risk assessment framework (Standards Australia 2009) to determine management outcomes in circumstances where there is considerable uncertainty and a lack of detailed data to describe coastal changes. Both describe circumstances relevant to vulnerability assessment for land systems and landforms along the Gascoyne coast. A similar approach has been adopted in this report by using a combination of structure and condition to determine vulnerability of land systems and landforms to existing and projected changes in metocean forcing. The vulnerability estimates are subsequently linked to broad estimates of the likelihood of environmental changes occurring. Vulnerability rankings then may be used to establish consequence and risk tables for the coastal land systems and landforms for a more detailed risk analysis that is not undertaken in the context of this report. However, it does provide an indication of further information requirements.

Risk assessment is commonly undertaken in an established framework, such as the principles and guidelines within AS/NZS ISO 31000 (Standards Australia 2009). Assessment provides an estimation of the likely consequences arising from occurrence of a hazardous event, ranging from insignificant to catastrophic outcomes. Estimations of the likelihood of the event occurring (Table 7-1) are based on limited experience with hazard identification, description and mitigation within the region of interest. The hazard estimates are used in consequence tables such as that presented by Australia Pacific LNG (2010) to examine the likelihood of health, safety and environmental consequences of different types of hazards (Table 7-2). They are prepared as part of Environmental Impact Statements (EIS) for major development proposals in Australia. The method subsequently enables the consequences of hazards impacting on the environment to be prioritised and considered in a full risk assessment. In this respect the framework provided by AS/NZS ISO 31000 guidelines (Standards Australia 2009) has relevance to the State Planning Policy 2.6 (WAPC 2003). Regardless of risk a full hazard and risk assessment is required for all development under existing State Government coastal planning and management policies.

Table 7-1: Probability Table Based on Metocean Forcing and Geologic Records (Source: Rollason *et al.* 2010)

Probability	Likelihood
Almost Certain	There is a high possibility the event will occur as there is a history of periodic occurrence
Likely	It is likely the event will occur as there is a history of casual occurrence
Possible	There is an approximate 50% chance that the event will occur
Unlikely	There is a low possibility that the event will occur. However, there is a history of infrequent and isolated occurrence
Rare	It is highly unlikely that the event will occur, except in extreme circumstances which have not been recorded historically.

Steps in the framework provided by AS/NZS ISO 31000 guidelines presuppose the availability of a wide variety of metocean, geomorphologic, social, cultural and economic information. Advisedly, collation of the physical information required for a full risk analysis would be based on a comprehensive review of available data to identify gaps and directed to enable:

- Detailed consideration of potential impacts of metocean processes (waves, winds, water levels, tropical cyclones and river discharge), including geotechnical survey (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) where appropriate. This is most likely to be where it affects elements or landforms with lower integrity of the natural structures or limited natural resilience.

- Determination of the potential impacts of extreme metocean events (such as storms) on these elements or landforms based on geological and historical (measured and surrogate) information as well as modelling of projected future extreme events.
- Identification of sediment sources, sinks and key transport pathways as a first step to determine the rate of coastal change and the potential impact of any proposed land through modification of the coastal sediment budget and its affect on the most unstable landforms.

Table 7-2: Health, Safety and Environment Consequence Categories for Critical and Catastrophic Levels of Risk (Source: Australia Pacific LNG 2010: p6)

	Impact to company personnel	Natural environment	Community damage/ impact/ social/ cultural heritage
Catastrophic	Multiple fatalities ≥4 or severe irreversible disability to large group of people (>10)	Long term destruction of highly significant ecosystem or very significant effects on endangered species or habitats	Multiple community fatalities, complete breakdown of social order, irreparable damage of high value items of great cultural significance. Adverse international or prolonged (>2 weeks) national media coverage
Critical	1-3 fatalities or serious irreversible disability (>30%) to multiple persons (<10)	Major off-site release or spill, significant impact on highly valued species or habitats to the point of eradication or impairment of the ecosystem. Widespread long-term impact	Community fatality. Significant breakdown of social order. Ongoing serious social issue. Major irreparable damage to highly valuable structures/items of cultural significance. Adverse national media coverage (>2 days)

7.4.1. Data Requirements

Data requirements include:

- Baseline coastal monitoring information such as shoreface and beach profiles should be collected for reaches of coast supporting infrastructure and where there is increasing use of the coast for tourism and recreational purposes where limited historic information is available.
- It is recommend LiDAR mapping of the inshore waters be completed to provide a wider context for available bathymetric information and provide a more complete assessment of natural resources, including sediment availability and distribution. Detailed inshore bathymetry for management of the inshore is available for parts of the coast, particularly in the vicinity of townsites and along the Ningaloo coast. The LiDAR is considered to be important because it would enable detailed interpretation of marine habitats and sediment movement adjacent to an area subject to increased settlement and land use pressure.
- Coastal sediment budget information, including determinations of approximate volumetric rates of sediment transport and identification of sediment sources and sinks, at appropriate locations such as Quobba and Monkey Mia.

- Determinations of the elevation and coverage of underlying rock are required for sites supporting urban-rural development and infrastructure that may be located on unconsolidated sediments overlying bedrock surfaces. Full geotechnical survey using drilling or other appropriate technique is recommended for these sites.

7.4.2. Other Requirements for Management Purposes

Other requirements for management purposes include:

- Identification and costing of ongoing management requirements at developed sites as well as those proposed for development or increased land use.
- Determination of potential migration or retreat of unstable landforms and the potential impacts of landform change on existing and proposed development.
- Identification of costs and allocation responsibility for management of coastal protection and stabilisation works, such as engineered structures and sediment bypassing, for the adjacent coast, as well as for ongoing coastal monitoring, maintenance and management of the site.
- Strategies to respond to metocean events and other site disturbances of various frequencies and magnitudes.

7.5. RECOMMENDATIONS FOR THE AREAS OF PLANNING INTEREST

7.5.1. General Advice

Compartments or cells with a high vulnerability ranking were areas where the potential effect of metocean processes was considered a major constraint to development due to weakness of the natural structures or poor natural resilience. These areas potentially require high ongoing management requirements and typically are suitable for limited development. Some consideration may be given to setting this land aside for the purposes of coastal protection and hazard mitigation. Sufficient justification to address major constraints usually occurs only if there is a very strong economic and social imperative, such as large-scale infrastructure requiring coastal access for marine-based industries, major harbours or port facilities. Detailed investigations are recommended as the basis for establishment of such infrastructure, including geotechnical studies (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique), sediment budget analysis (approximate volumetric rates of sediment transport including sources and sinks) and numerical modelling (such as wave, current and sediment transport modelling to provide further context for the volumetric rates of sediment transport).

Additionally, it is advised that development requires consideration of long-term management responsibility for coastal protection and stabilisation works, as well as for ongoing maintenance and management of the site. Required stabilisation works should be identified and costed. Proposed developments should not devolve responsibility for protection works, or ongoing maintenance (such as bypassing), to the State or Local Government.

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Appendix A The Project Brief

THE BRIEF

Development of Sediment Cell Concepts for the

1) Shires of Gingin to Dandaragan,

2) Shires of Coorow to the Shire of Northampton, and

3) Shires of Shark Bay, Carnarvon and Exmouth

1. BACKGROUND

Previous investigations undertaken to identify coastal stability and susceptibility to change along parts of the Western Australian coast have been conducted in consultation with officers from the Departments of Planning, Transport, Environment and Conservation and the Geological Survey of Western Australia, as well as private industry groups, to assist the State Government provide informed planning guidance for regional and sub-regional strategic planning. The investigations parallel procedures developed in the United Kingdom and have resulted in development of an approach that provides consistency and coherence in its application across planning scales as well as from place to place. This Brief is for a project to link the areas examined and provide comprehensive information for the coast between the Shire of Gingin and the Exmouth Gulf. The intention of the project is to expedite decision making for planning and management of coastal and inshore marine resources.

Detailed investigations have been completed for the coast between Cape Naturaliste and Lancelin, and for the Batavia Coast between Leander Point and Cape Burney. This Brief will result in the extension of these investigations to the coastal areas between Lancelin and Kalbarri and broadly in the Gascoyne region. The areas for investigation are under increasing pressure for development and they require strategic planning guidance for future land use. Such guidance is a not readily available for all sections of the coast proposed for examination.

Further north, the Midwest Region is under pressure for coastal development in towns such as Horrocks, Port Gregory and Kalbarri. The region is becoming more attractive to retirees for the lifestyle opportunities and to those gaining employment in industrial and mining sectors in and around Geraldton. Tourism is a key driver for growth in the Gascoyne region and areas need to be identified that support this landuse so not to negatively impact on the natural environment. Appropriate locations for coastal nodes for recreational and tourism development need to be determined, such as those designated along the Ningaloo coast.

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Appendix B Glossary

	Term	Explanation
A	Alongshore	Marine and beachface processes operating along the coast are *alongshore* processes. The term alongshore also indicates direction.
	Arcuate shoreline	An *arcuate shoreline* is an embayed shoreline. In plan form the arc is concave to shoreward and may be a half-heart shape, occasionally referred to as a zeta-form, or semi-circular in form. The shape provides an indication of ocean processes affecting the shore of the embayment.
	Aspect	*Aspect* is the direction to seaward the coast faces. It is estimated in the centre of the coastal feature being examined and at right angles to the trend of the coastline in plan. The direction faced by the coast determines the prevailing and dominant metocean processes to which it is susceptible. For example, unsheltered NW facing coasts in the region are fully exposed to storms from that direction.
	Avulsion	*Avulsion* is the switching, or rapid migration, of a river channel location and abandonment of the prior channel. This behaviour may be common on large active delta systems.
B	Backshore	The most landward extent of bare, unvegetated beach is the *backshore*. It is a zone infrequently inundated by storm waves active during phases of extreme, higher-than-average sea-level conditions.
	Backbarrier	The most landward barrier landforms, particularly the coastal dunes furthest inland, sandflats and washover lobes extending into coastal lagoons are referred to as *backbarrier* features.
	Barrier	*Barriers* are relatively narrow strips of sand parallel to the mainland coast. The sands occur in distinct lenses deposited at a particular geological time, with the most recent barriers being formed during the Holocene, over the past 10,000 years. Landforms associated with barriers extend from the inner continental shelf include those of the active shoreface, beach and dunes along the coast. The suite of dunes comprising the landform may be referred to as *barrier dunes*.
	Beach profile	The beach profile is the cross-sectional shape of the beach from the seaward toe of the foredune or upper reach of wave action to the seaward limit of currents generated by breaking waves. In a seaward sequence the profile may include the following morphology: berm, beachface, step, trough, ripples and bar. It is comprised of several zones defined by the dominant processes, including the subaerial beach, swash zone, and nearshore zone.
	Beach response	The response of a beach to metocean forcing, human intervention and/or alteration in sediment supply.
	Beach rock	A friable to well-cemented sedimentary rock, formed in the intertidal zone.
	Beach type	Beaches are categorised according to their environmental setting and profile configuration. In the context of this report the first distinction is between beaches located in *sheltered* or *exposed* locations where the most common wave conditions are less or higher than 50cms. *Sheltered beaches* have profiles that are flat or rounded. Both exposed and sheltered beaches may overlie a rocky substrate. These are *perched beaches*.
	Birrida	Flat, raised pan, often elliptical in shape. These are commonly lagoons and tidal creek systems that were previously connected to the ocean.
	Blowout	In plan form a *blowout* has a parabolic form with a width greater than its length. Blowouts occur in partially vegetated foredunes. A *blowout* forms when a patch of protective vegetation is lost, allowing strong winds to "blow out" sand and form a depression.
C	Calcarenite	A limestone consisting predominantly of sand-sized carbonate grains.

	Chenier	A discrete, elongated beach ridge, comprised of marine sand or shell, which is stranded on a coastal mudflat or marsh, roughly parallel to the shore. The ridges may be vegetated. . When cheniers are distributed across a wide plain on a prograding shoreline, that feature is called a 'chenier plain' (OzCoasts)
	Chenier spit	A chenier that is joined to the mainland on one end but not the other, thus forming a spit.
	Cliffed dune	The seaward margin of a foredune or frontal dune may be cut by coastal erosion that results in the formation of a low sandy cliff.
	Coastal compartment	A coastal *compartment* is a component of the geological framework of the coast. It is an area of coast bounded alongshore by large geologic structures, changes in geology or geomorphic features exerting structural control on the planform of the coast. Compartments contain a particular Land System or landform association depending on the scale at which they are being described.
	Continuous reef	*Continuous reef* occurs where an unbroken line of reef extends parallel to the shore for at least the length of the coastal feature under consideration.
	Curvilinear (rounded) beach	Beaches in sheltered environments subject to a relatively high wave regime compared with other sheltered beaches may have an upwardly convex or concave beachface profile. These are curvilinear in form and may grade to a step at the seaward limit of the swash zone.
	Cuspate foreland	On the Ningaloo coast of Western Australia *cuspate forelands* are triangular-shaped accretions of sand extending seawards in the lee of an offshore reef. *Cuspate forelands* principally develop in response to longshore movement of sediment and hence are highly susceptible to changes in metocean processes.
	Delta	A landform comprised of branched or interleaved channels and alluvial deposits occurring at the mouth of a river, due to high river discharge and sediment supply.
D	Discontinuous reef	*Discontinuous reef* occurs where the line of reef extending parallel to the shore has gaps or breaks over the length of the coastal feature under consideration. The length of gaps along the coast under consideration is significantly less than that occupied by reef.
	Dissipative beach	A *dissipative beach* is one in which wave energy is substantially expended as the wave moves from its break point to the shore. Multiple lines of breakers are present. On an exposed wave-dominated coast wave heights exceed 2.0m and the profile includes a flat beachface with multiple bars and troughs in the inshore zone. In a sheltered environment where wave heights are less than 0.25m the profile is planar, with a very broad sub-tidal terrace.
	Division	A *division* is a subdivision of a broad climatic zone. The unit provides an overview of the whole state suitable for maps at scales of about 1:5,000,000. For example, wet-dry tropics and sub-tropical areas are subdivisions of the tropical zone in north Western Australia.
E	Eolianite	*Eolianite* is weakly cemented rock that is commonly comprises calcareous dune sand derived from a marine environment. The stratigraphy of the dunes in which the eolianite has formed is usually present in outcrops.
	Ephemeral creek	River or stream catchments with intermittently flowing streams that are locally important at times of high flood discharge, particularly when they interact with coastal processes.
	Episodic, transgressive dune barrier	An *episodic, transgressive dune barrier* comprises nested blowouts and/or parabolic dunes. The dunes commonly form a ridge of irregular height along the coast. The ridge and its dunes are the surface features of the barrier which also extends offshore as a marine deposit of sands with a similar mineral composition to those found in the dunes.
	Exposed beach	*Exposed beaches* are open to the full effects of metocean processes. The beaches experience average wave heights of over 1 metre and are considered to be wave dominated. They have reflective, transitional or dissipative profile features.

F	Flat beach	*Flat beaches* occur in very sheltered environments, those with a modal wave height of less than 25cms. The beach profile is likely to have a negative exponential shape with a small, narrow, upwardly concave beachface grading to a flat low tidal and wide intertidal terrace that terminates in a steep drop to deep water.
	Flood basin or flood storages	Those very low-lying parts of a floodplain that are important for the temporary storage of floodwaters during passage of a flood.
	Floodplain	The undulating portion of a river valley, adjacent to the river channel, which is covered with water when the river overflows during floods
	Floodway	Those areas where a significant volume of water flow during floods. They are often aligned with obvious naturally defined channels. Floodways are areas which, even if only partially blocked, would cause a significant redistribution of flood flow. This may in turn adversely affect other areas. They are often, but not necessarily, the areas of deeper flow or the areas where higher velocities occur.
	Foredune	A *foredune* is a small coastal dune or low ridge. Foredunes are commonly less than 10m in elevation, located parallel to the shoreline and along the landward margin of a beach and stabilised mainly by pioneer vegetation. Foredunes are built through pioneer vegetation trapping of windblown sand directly from the beach. They build in height until the vegetation is destroyed; blowouts are formed and migrate landwards.
	Foreshore	The *foreshore* of a beach includes the berm, swash zone and lower intertidal zone.
	Frontal dune	Blowouts and parabolic dunes closest to the shore and immediately landward of the backshore where foredunes have formed or potentially could form are the *frontal dunes* or *primary dunes*. Absence of a foredune supporting pioneer species and scarping (cliffing) of the frontal dunes is indicative of a depleted sediment supply and coastal erosion.
G	Geologic framework	The *geologic framework* of a coastal area is the surface topography or geometry of bedrock in a designated area that interacts with metocean processes and the sediment transport regime to affect the distribution of unconsolidated sediments and the development of coastal landforms.
H	Hind Dunes	*Hind dunes* are those landward of the frontal or primary dunes.
	Holocene	The *Holocene* is a geological epoch that began approximately 12,000 years ago. It is an interglacial period of atmospheric warming and sea level rise. During the last 10,000 years before present sea level rose from below 50m to a peak of 1 to 2 metres above its present level approximately 6,000 years ago. The modern coast developed in response to this rise and subsequent fall.
I	Induration	The process of becoming hard. In geomorphic terms, this is commonly associated with the calcification of marine sediments to form cohesive or sedimentary rock deposits.
	Inshore	In the context of this report the term *inshore* refers to waters and seabed less than 25m deep adjoining the shore. The area commonly includes offshore reefs and the lagoons they impound.
	Instability	*Instability* refers to the current condition of similar landforms from different places. For example, it may be apparent as the percentage of vegetation cover on different dune fields, the completeness of foredune development on sandy beaches or differences in the historical records of shoreline movement on beaches.
	Isobath	An *isobath* is a submarine contour line indicating points of equal depth on a bathymetric map.
	Intermittent reef	*Intermittent reef* occurs where outcrops are uncommonly distributed in waters along the coastal feature under consideration.
J		
K		

L	Lagoon	A coastal *lagoon* is a water body sheltered from the full impact of oceanographic processes by an offshore reef or dune barrier.
	Land system	A *land system* is an area of characteristic landform patterns suitable for mapping at regional scales of 1:50,000 to 1:100,000. Several landforms form a landform pattern which in turn comprises a land system.
	Landform	A *landform i*s a natural feature of the Earth's surface. Landforms range in size from small features apparent at a local scale to large structures apparent at a land system or regional scales. In the context of this report the term is used to describe features apparent at a local scale of 1: 500 to 1:25,000.
	Landform association	A *landform association* is a group of contiguous landforms that are associated in some way, commonly by shared location or age structure. For example, a Holocene sandy beach perched abutting an older dune and perched on a Pleistocene limestone platform..
	Landform element	Each landform is made up of geometrically recognised components or *landform elements*. For example a blowout dune includes a slack, side walls, dune crest, slipface and toe slope.
	Landform pattern	A *landform pattern* is a group of landforms of a common geologic age that is the landform part of a land system. For example, a Holocene progradational barrier (landform system) is a low-lying plain (landform association) comprised of a sequence of foredune ridges, a beach and shoreface morphology.
	Lithified chenier	A chenier that has become cemented through a combination of induration and compaction.
	Littoral	The adjective *littoral* is used to designate the beachface and adjoining inshore areas of a sandy beach as well as the processes affecting them. The *littoral zone* extends from the spring high tide line to submarine areas affected by swash processes.
M	Mainland beach	Mainland beaches are apparent where a thin deposit of marine sands abut Pleistocene or older landforms. In some instances the sand may be sub-tidal and abut a platform or cliff.
	Metocean	*Metocean* is an abbreviation of meteorological and oceanographic. Hence *metocean processes* include all atmospheric and oceanographic processes such as storms, winds, waves, currents and tides.
	Mobile dunes	*Mobile dunes* are apparent as partially vegetated and open sand masses associated with blowouts, parabolic dunes and sand sheets.
	Morphodynamic	The coastal system is one in which morphology, sediments and processes are dynamically linked such that change in one will be associated with change in the others. This is referred to as a *morphodynamic* system.
	Morpho-stratigraphic	The term *morphostratigraphic* is used to indicate linkages between coastal morphology and stratigraphy.
	Morphology	*Morphology* describes landform associations or systems comprised of unconsolidated sediment.
N	Natural Structure	*Natural structures* are geologic or geomorphological features, such as a rocky promontory or a sandy barrier.
O	Offshore	The term *offshore* is used in the report to designate either ocean seaward of the 30m isobath or shallower water seaward of the zone in which waves break.
P	Parabolic dune	In plan, a *parabolic dune* is a long U-shaped dune with long trailing arms (the vertical part of the U) pointing to windward. Parabolic dunes are common in the Gascoyne coast region, where dune migration commonly occurs over a low plain or flat marl surface.
	Pavement	*Pavement* is a rock surface outcropping at an elevation close to the surrounding seabed. It may be part of a mixed sand and rock seabed, or patched reef, where it is irregular in form and elevation.
	Perched beach	Sandy beaches on which the sand overlies a rock pavement, beachrock ramp or rock platform is referred to as *perched beaches*.

		Under an engineering definition beaches immediately landward of a rock outcrop but separated from it by a narrow lagoon may also be classed as perched beaches.
	Pioneer vegetation	Herbaceous and grassy vegetation that first colonises the storm wrack line along the backshore as well as disturbed sites in dunes to landward is *pioneer vegetation*.
	Platform	A gently sloping surface produced by wave erosion, extending into the sea from the base of a wave-cut cliff.
	Pleistocene	The *Pleistocene* is the first geological epoch of the Quaternary Period and spans geologic time from approximately 2.6 million to 12,000 years before present. It is a time of repeated glaciations and sea level fluctuation on Earth.
	Pocket beach	A *pocket beach* is a small beach fixed between two headlands. Pocket beaches are commonly crescentic in plan, with the concave edge toward the sea. There is very little or no exchange of sediment between the beach and the adjacent shorelines.
	Prograded barrier	A succession of multiple foredune and/or beach ridges on the open coast and in sheltered waters form low-lying plain referred to as a *prograded barrier*. The plain may be features of a composite barrier where they merge with transgressive dune fields to landward or are overlain by blowouts along their seaward margin.
	Province	A *province* is an area defined on geological (lithology, topography and stratigraphy) or geomorphologic (major land systems) criteria suitable for a regional perspective at a scale of about 1:1,000,000. Originally described by CSIRO (1983).
Q	Quaternary	The *Quaternary* Period is the most recent of the three periods of the Cenozoic Era in the geologic time scale and has extended from approximately 2.6 million years ago to the present. The Quaternary includes two geologic epochs: the Pleistocene and the Holocene Epochs
R	Receded barrier	On coasts where sediment supply is limited *receded barriers* are thin marine sand deposits in narrow dunes that overlie estuarine, backbarrier or mainland features which outcrop at the shore.
	Reef	In the context of this report the term *reef* refers to any rock outcrop with an elevation above the surrounding sea bed. Herein, reef is described as being *continuous, discontinuous* and i*ntermittent* or as *pavement.*
	Reflective beach	A *reflective beach* is one on which incident waves are reflected seaward from a steep beachface following backwash run out. Reflective beach profiles are characterised by a berm or berms, a steep beachface, a step at the bottom of the swash zone and a deep, planar inshore zone. They are common features of coasts with a modal wave height of approximately 0.5 to 1.5 metres but also are observed on beaches comprised of coarse sediment and subject to larger waves.
	Region	A *region i*s an area with a characteristic pattern of land systems that differentiates it from adjacent areas. The unit is suitable for mapping at scales of approximately 1:250,000. This differs from the definition provided by CSIRO (1983) and Schoknecht *et al.* (2004).
	Rhythmic shoreline	An uninterrupted sandy shoreline is considered to be *rhythmic* when it has a sinuous plan form with shallow embayments separated by shoreline salients.
S	Salient	Part of a sandy coast protruding seaward of the average trend of the shoreline.
	Sand sheet	A *sand sheet* is either a mass of mobile sand that has become detached from a blowout or parabolic dune and is moving freely across the landscape; or it is an area of bare sand where active blowouts and/or parabolic dunes have coalesced.
	Sediment cell	A coastal *sediment cell* is a section of coast and its associated nearshore area within which the movement of sediment is apparent through identification of

		areas which function as sediment sources, transport pathways and sediment sinks. Classically, interruptions to movement of sediment within one cell should not affect beaches in an adjacent cell. However this is not always applicable to beaches in Western Australia where the major source of sediment is derived from offshore sources.
	Sheltered beach	*Sheltered beaches* are protected from the full effects of metocean processes by offshore reefs or by their aspect. The beaches frequently experience average wave heights of less than 1 metre and are considered to be dominated by fluctuations in sea level, particularly those associated with surge. They have flat profiles which may be segmented where longshore currents prevail, or rounded profile features under wave regimes relatively higher than those experienced on flat beaches.
	Shoreface	The *shoreface* is a zone extending seaward from the foreshore, beyond the breaker zone to the limit of wave movement of sediment. It is the zone in which the majority of sediment transport occurs.
	Shoreline	The shoreline is a discrete line along the coast. In the context of this report it is the High Water Line used in the Australian Oil Spills Response Atlas (OSRA) and described by Landgate (2006).
	Shoreline plan	The *shoreline plan* is a view of the shoreline shape from directly above so that its plan shape is readily apparent.
	Storm bar or storm ridge	Narrow sand (or gravel or shell) deposit developed to supratidal level by storm activity; occurs to landward of beach slope. It may be partially indurated. Storm ridges are similar in form to a chenier although commonly higher and may not sit on a muddy substrate.
	Storm bar retreat	Landward retreat of the storm bar or storm ridge. The process of retreat is commonly apparent by breaching of the ridge and development of washover fans on the shoreward side of the ridge
	Straight shoreline	A *straight shoreline* closely approximates a straight line over the length of coast under consideration.
	Stationary barrier	*Stationary barriers* are narrow, capped by blowout dunes overlying well developed backbarrier sandflats and washover lobes. Stationary barriers are commonly associated with coastal lagoons or adjoin alluvial flats to landwards.
	Stratigraphy	*Stratigraphy* is the study of geologic strata or layers of sediment.
	Substrate	The *substrate* is the surface on which a barrier sits. For example, the Holocene barriers forming the modern coast are commonly located on a coastal limestone surface of Pleistocene age.
	Subtidal terrace	A gently-inclined sedimentary accumulation feature that may be partially exposed at low tide. The subtidal terrace occurs seaward of the low tide level on the beachface.
	Susceptibility	*Susceptibility* is an estimate of the likelihood of a land system altering in structure over a planning horizon of 100 years. The estimate is based on a comparison of the existing structure with reported descriptions of the evolution of similar structures. Following Roy *et al.* (1994) for example, prolonged erosion of an episodic transgressive barrier complex may result in a change to a receded barrier.
	Swash	Swash describes the uprush and backwash of waves on the beachface of a sandy beach. The swash zone extends seaward from the limit of uprush down slope to include the step at the bottom of the beachface and the inshore area affected by backwash run out.
	Terrace response	Response of a subtidal terrace to metocean forcing, human intervention and/or alteration in sediment supply. A sub-tidal terrace may provide a buffer to sheltered coasts from changes in metocean forcing or extreme events, through reworking of sediments and adjustment of terrace width and depth, if there is sufficient capacity for the necessary provision or loss of sediment

	Tidal creek	Drainage channel carrying tidal water flows that incise tidal flats. Creeks may be meandering to birfurcating and their headwaters vary in function from erosional to depositional depending on interactions with sea level fluctuation and flood runoff from the hinterland.
	Tidal flat	Gently-inclined, tidally-inundated lowland connected to the shore by tidal channels. In this document the term mudflat has been applied to the area of tidal flat above mean sea level; and terrace to the mainly subaqueous landform below mean sea level for convenience. Tidal flat refers to the whole geomorphic system. Tidal flats are areas of marked interaction between rivers and tidal creeks, as well as surface run-off.
T	Time scales	The *long-term* times scale refers to coastal evolution and the *susceptibility* of land systems to change over geologic time, particularly over the geological epochs of the Quaternary Period; the Pleistocene and Holocene Epochs. The short-term time scale refers to factors affecting the *stability* of coastal landforms. These are linked to the 100 year planning horizon of the State Coastal Planning Policy (SPP No. 2.6) as follows: *Short-term*: 1 to 10 years *Intermediate-term*: 11 to 25 years *Long-term*: longer than 25 years
	Tombolo	A *tombolo* is a deposition landform in which an island is attached to the mainland by a narrow piece of land. Tombolos are developed by refraction, diffraction and longshore drift to form a spit or bar that connects the mainland coast to connecting a coast to an offshore island. Once attached, the island is then known as a tied island.
	Topography	In the context of this report t*opography* describes landform associations or systems comprised of rock
	Transgressive dunes	Blowouts and/or parabolic dunes migrating landward from the sediment source at the beach are *transgressive dunes* in that they bury older landforms (and infrastructure) as they migrate. Dune mobilisation takes place episodically hence the dunes may be overlain to form and episodic, transgressive barrier.
	Transitional beach	On exposed, wave-dominated coast sandy beaches may fluctuate in form between reflective and dissipative states as the wave regime alters between low and high wave extremes. Between these extremes the *transitional* state is one with profiles that have elements of both. Transitional sandy beaches are morphologically characterised by bars, troughs and rip current channels.
U	Unconsolidated sediments	*Unconsolidated sediments* are loose sediment particles such as gravel, sand, silt and clay that have not been lithified or consolidated into rock.
V	Vegetation cover	For a designated area *vegetation cover* is the proportion of the land surface covered by plants.
	Vulnerability	*Vulnerability r*efers to the likelihood of a land system or landform changing in response to changing metocean conditions. It is estimated as a combination of the long-term susceptibility and short-term instability of a coastal compartment or sediment cell.
W	Washover lobe	Under extreme storm conditions and high sea levels low barriers may be breached by waves that wash sediment from the beach onto lowland or into lagoons landwards of the barrier. The sediment is deposited in fans or *washover lobes.*
X		
Y		
Z	Zeta-form	A half heart-shaped bay, often due to headland control and a single prevailing direction of wave approach.
	Zone	*Zone* has two meanings. Firstly, in a land system context it is a broad section of the Australian Coast based on climate, and separating the tropical from temperate zones. These

		are referred to as regions by CSIRO (1983) and Schoknecht *et al.* (2004). Secondly, at a more detailed scale zone describes a small area where a particular suite of coastal processes and landforms are present. For example, the nearshore zone is where waves, wave driven currents and tides determine the pattern of bars and beach shape.

Further information of the terminology used in this report may be obtained from:

- Kearey P. (2002) *Dictionary of Geology*. Penguin Reference, Penguin, UK.
- New South Wales Goverment. (1986) *Floodplain Development Manual*. New South Wales Goverment PWD 86010.
- Schwartz ML. (2005) *Encyclopaedia of Coastal Science*. Encyclopaedia of Earth Science Series. Spinger Reference, Springer, NY.
- Semeniuk V. (1986) Terminology for geomorphic units and habitats along the tropical coast of Western Australia. *Journal of the Royal Society of Western Australia*, 68 (3): 53-79.
- United States Army Corps of Engineers: USACE. (2003) *Coastal Engineering Manual Appendix A: Glossary of Coastal Terminology*. EM 1110-2-1100.

Appendix C Coastal Land Systems: Murchison River to Locker Point

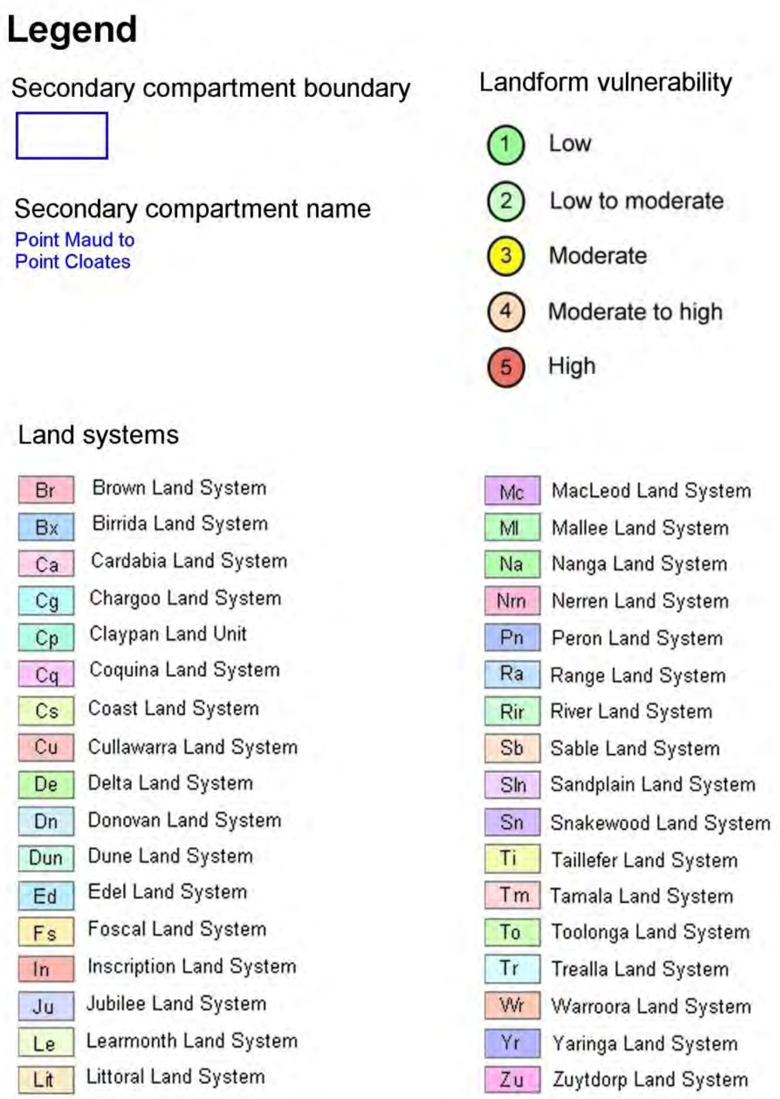

Figure C - 1: Compartment and Land System Map Legend

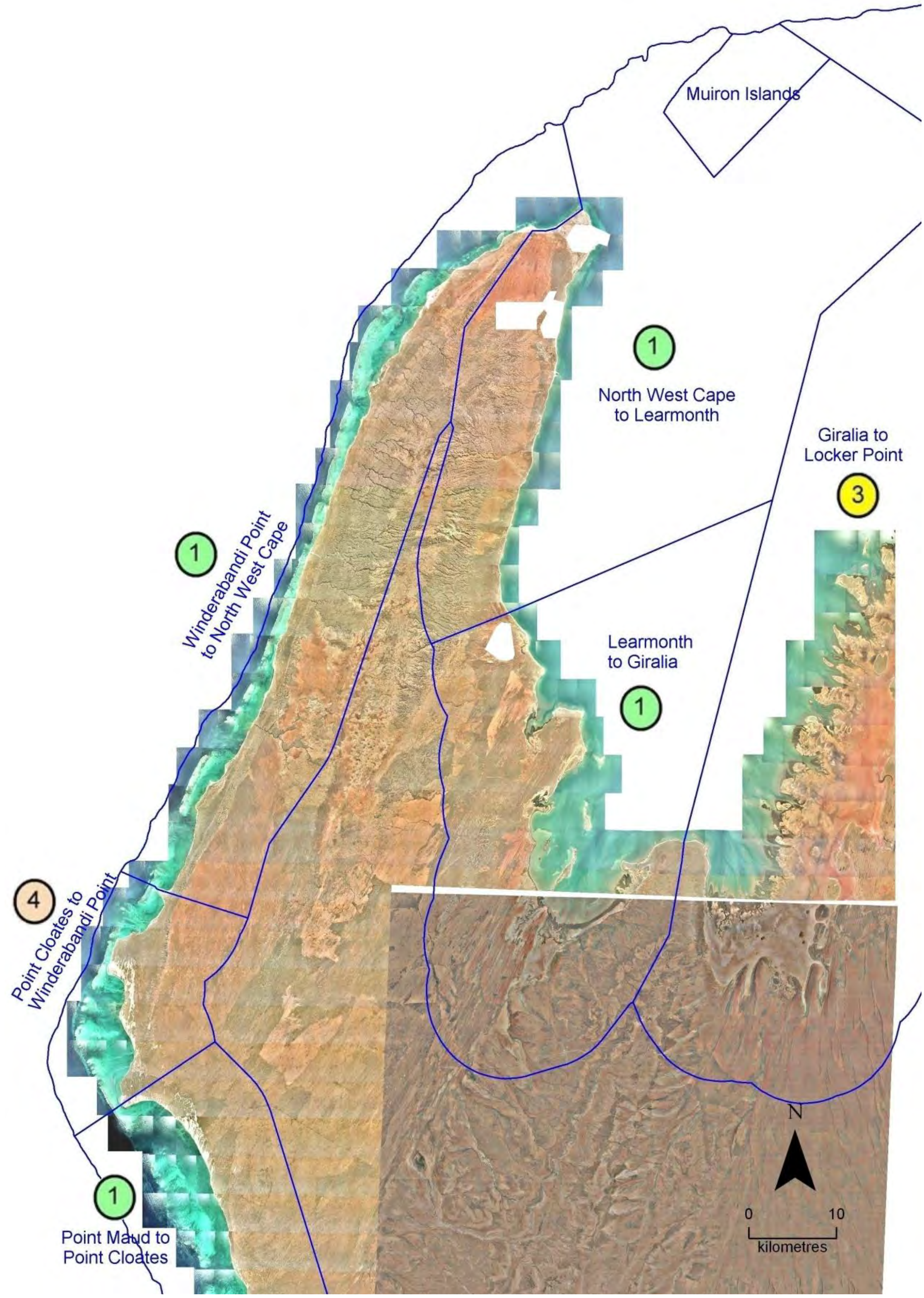

Figure C - 2: Vulnerability for Secondary Compartments from Point Cloates to the Eastern Boundary of the Study Area

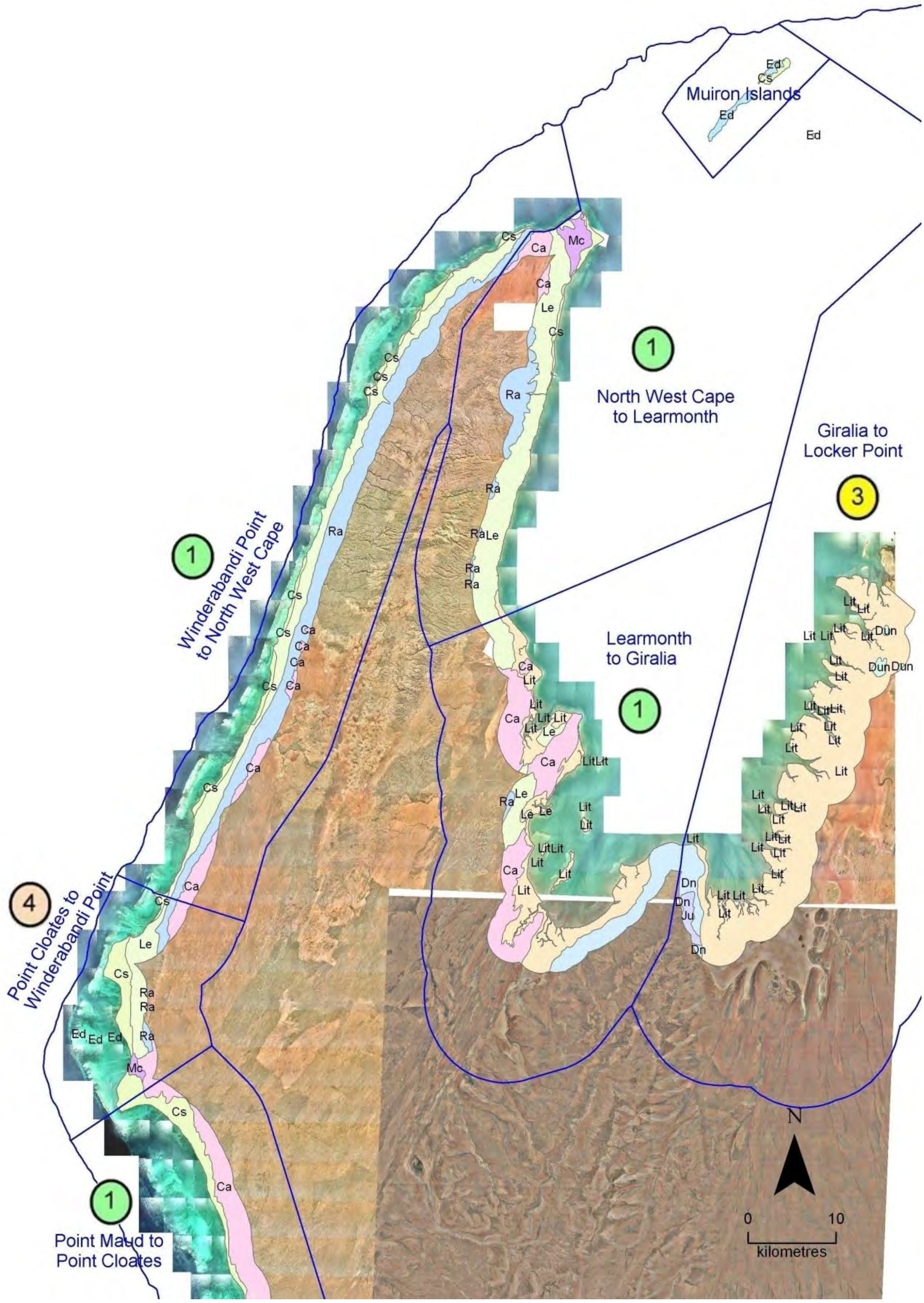

Figure C - 3: Land Systems for Secondary Compartments from Point Cloates to the Eastern Boundary of the Study Area

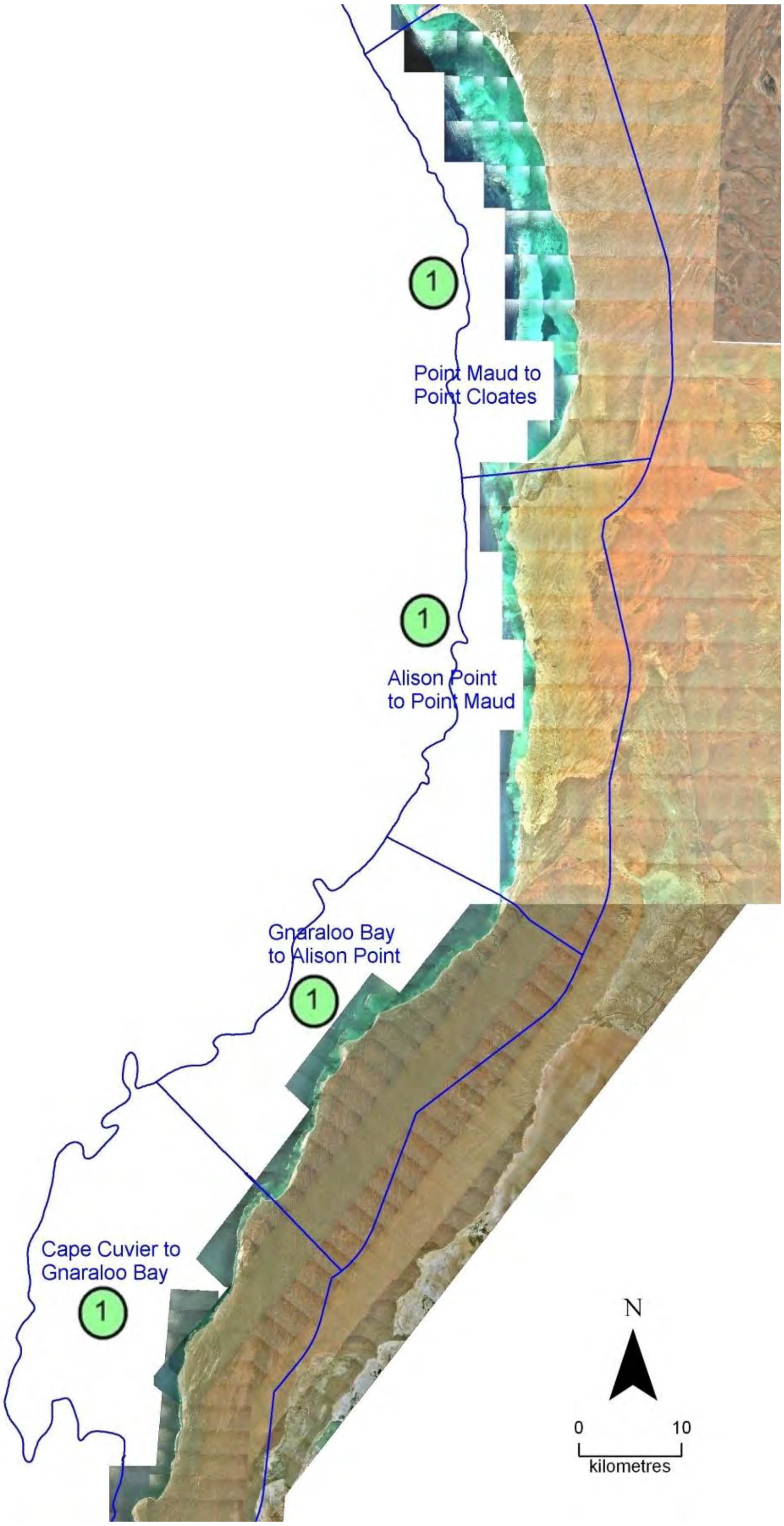

Figure C - 4: Vulnerability for Secondary Compartments from Gnaraloo Bay to Point Cloates

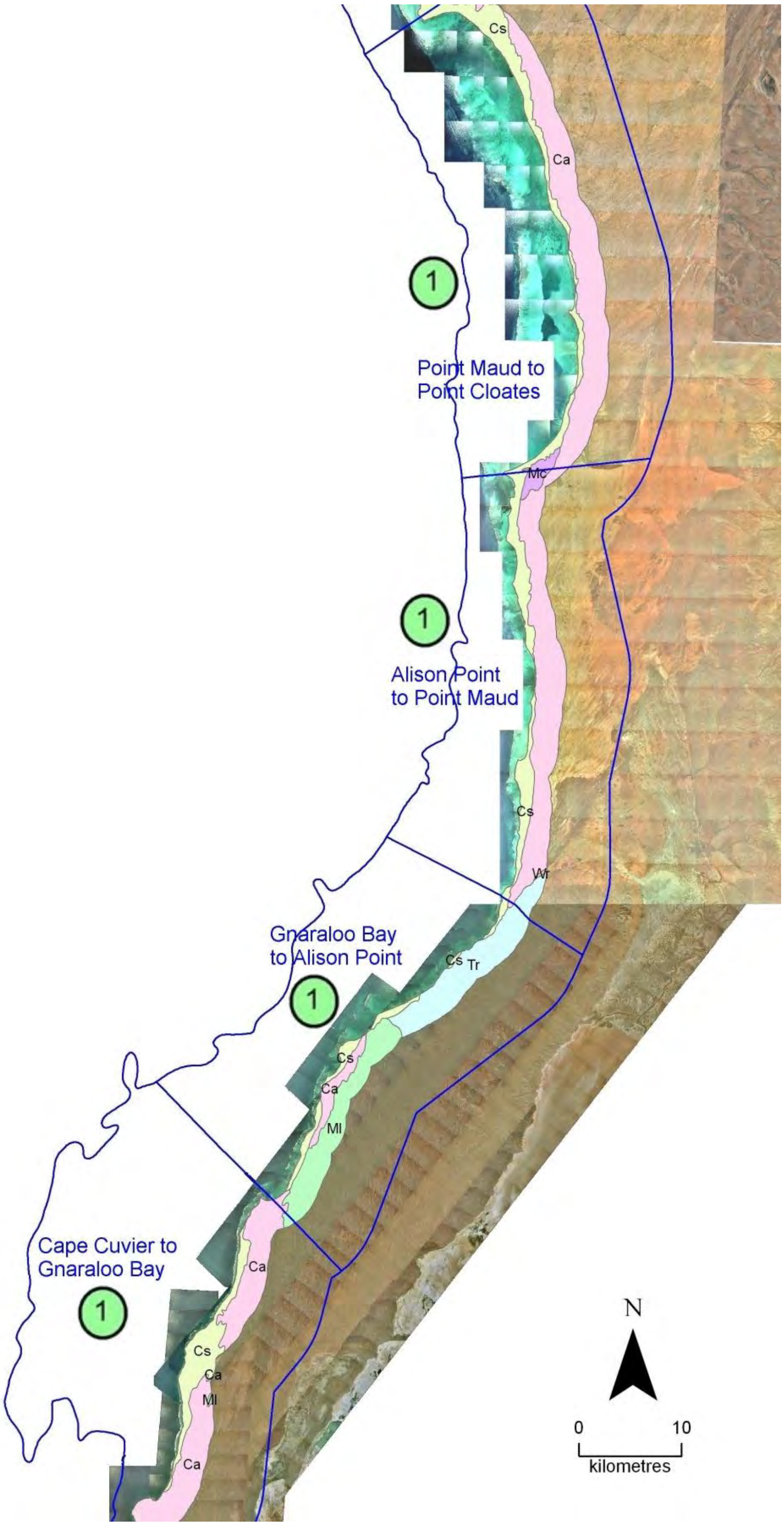

Figure C - 5: Land Systems for Secondary Compartments from Gnaraloo Bay to Point Cloates

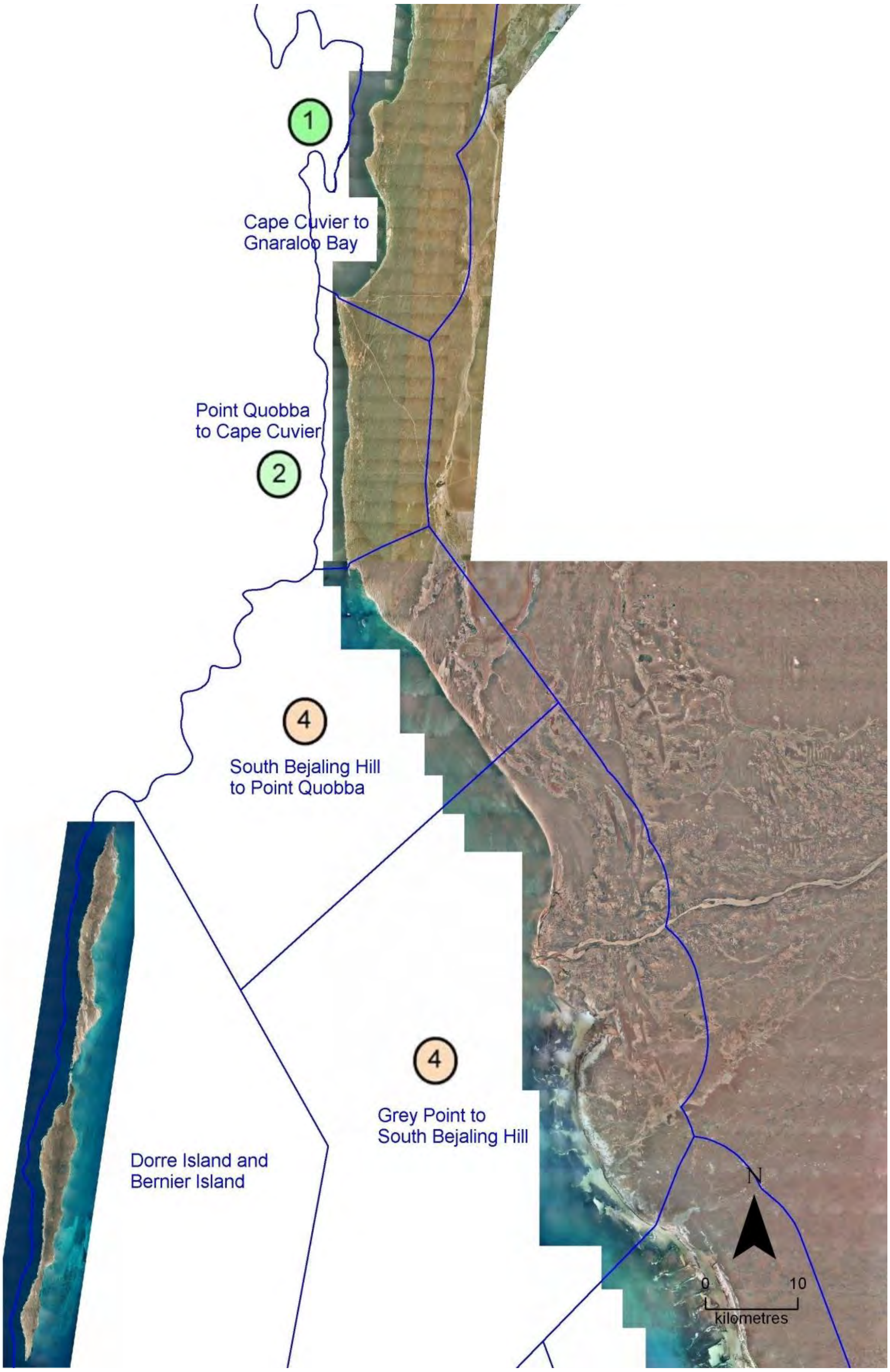

Figure C - 6: Vulnerability for Secondary Compartments from Grey Point to Gnaraloo Bay

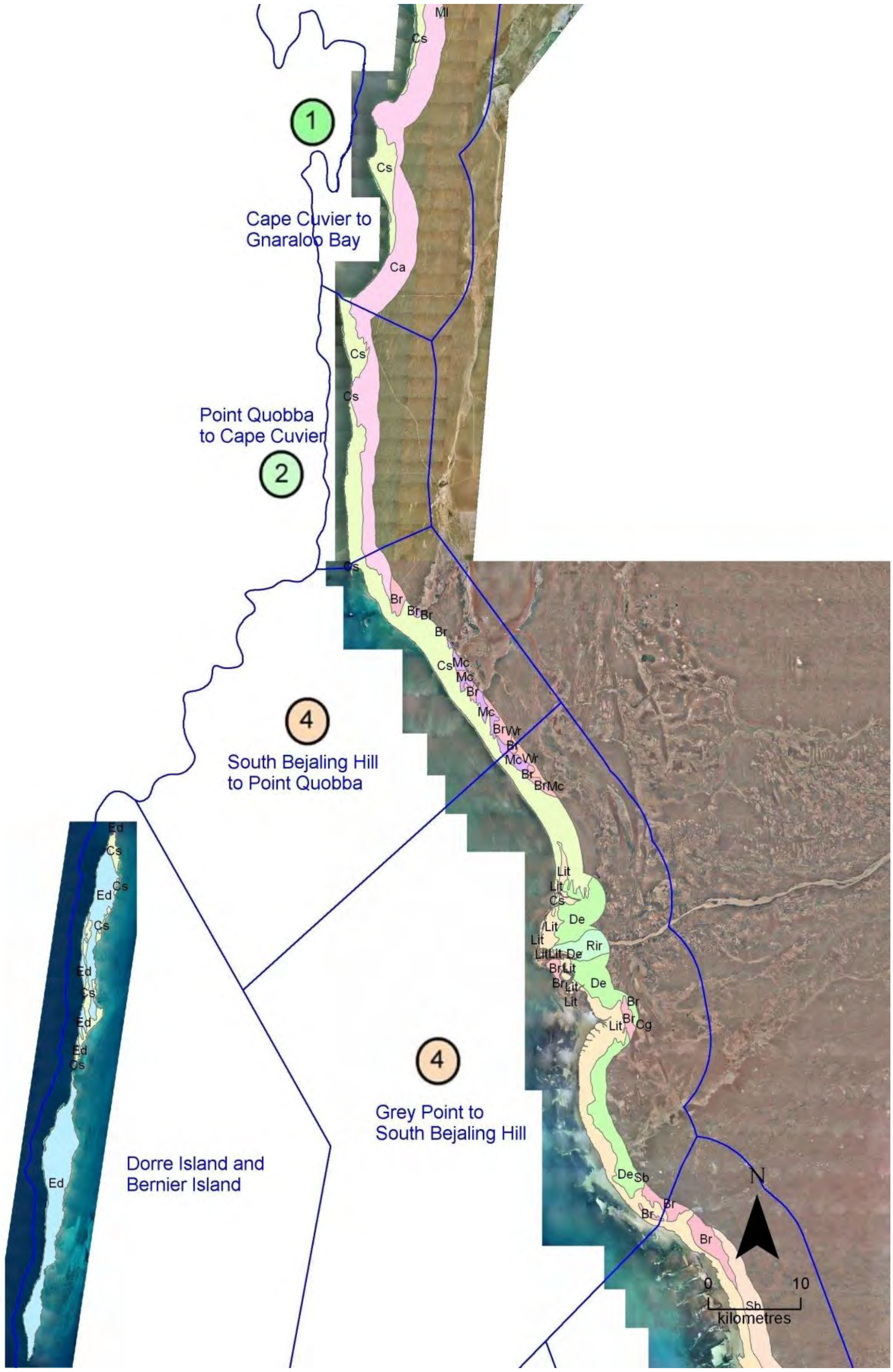

Figure C - 7: Land Systems for Secondary Compartments from Grey Point to Gnaraloo Bay

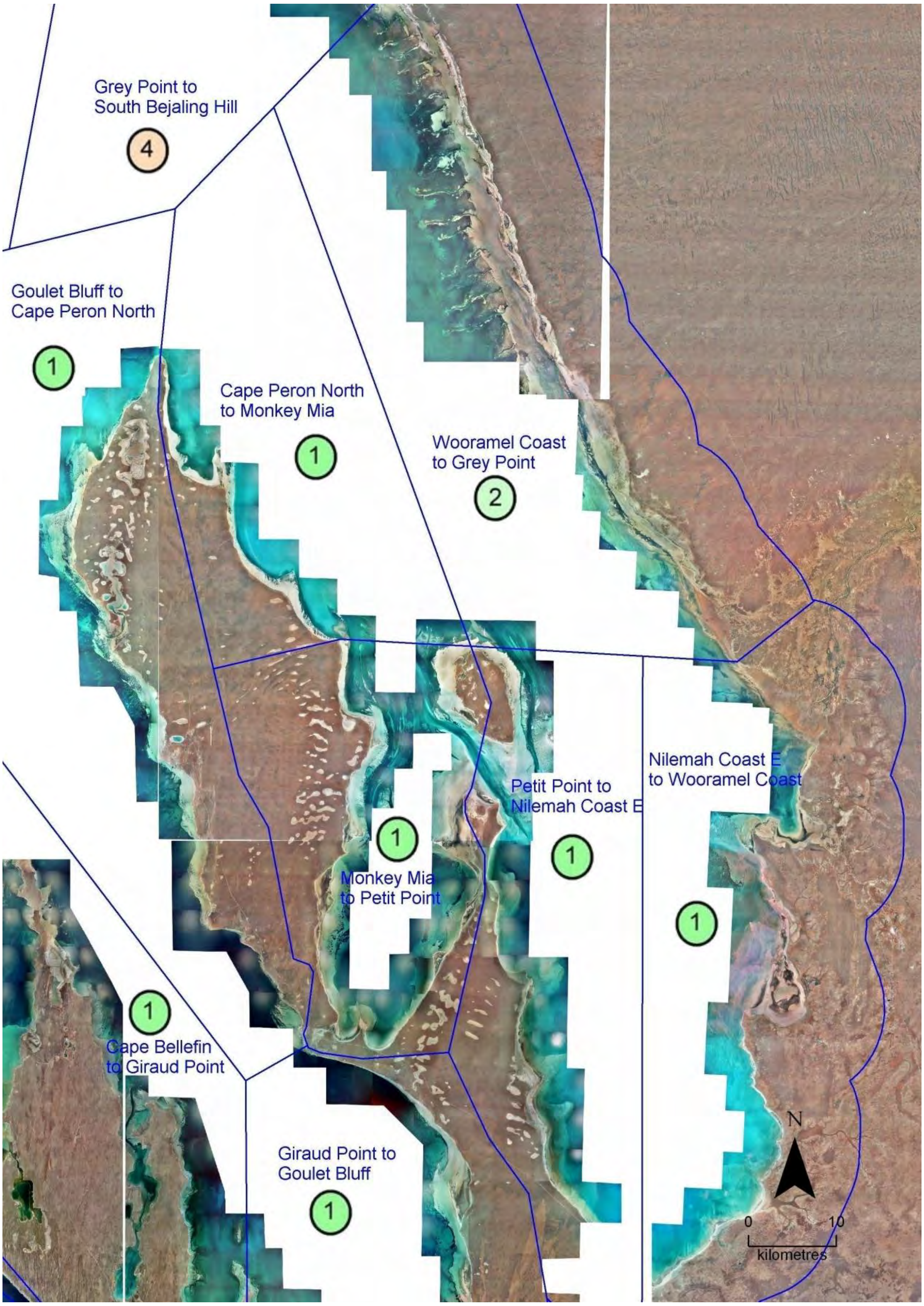

Figure C - 8: Vulnerability for Secondary Compartments for Eastern Shark Bay

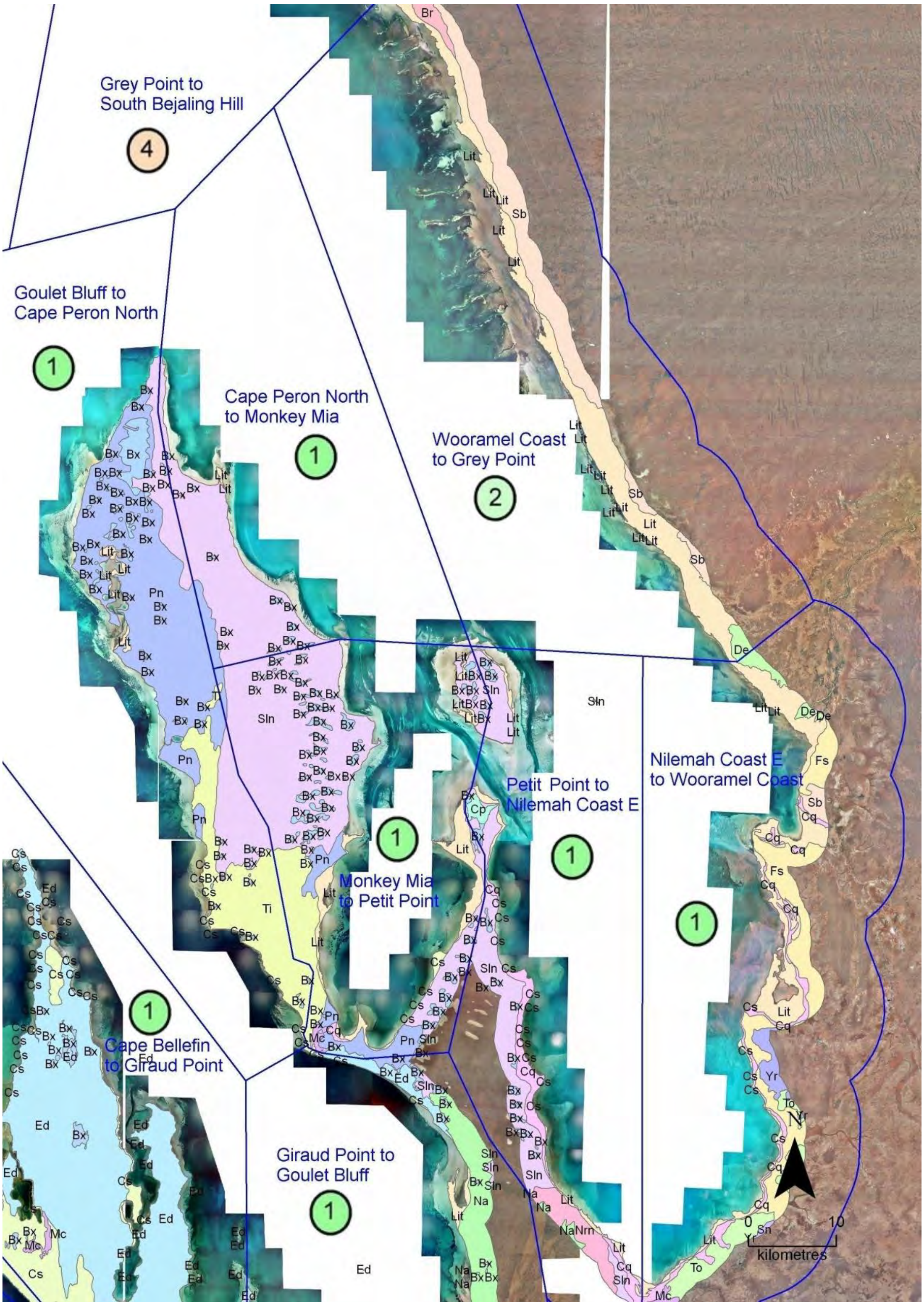

Figure C - 9: Land Systems for Secondary Compartments for Eastern Shark Bay

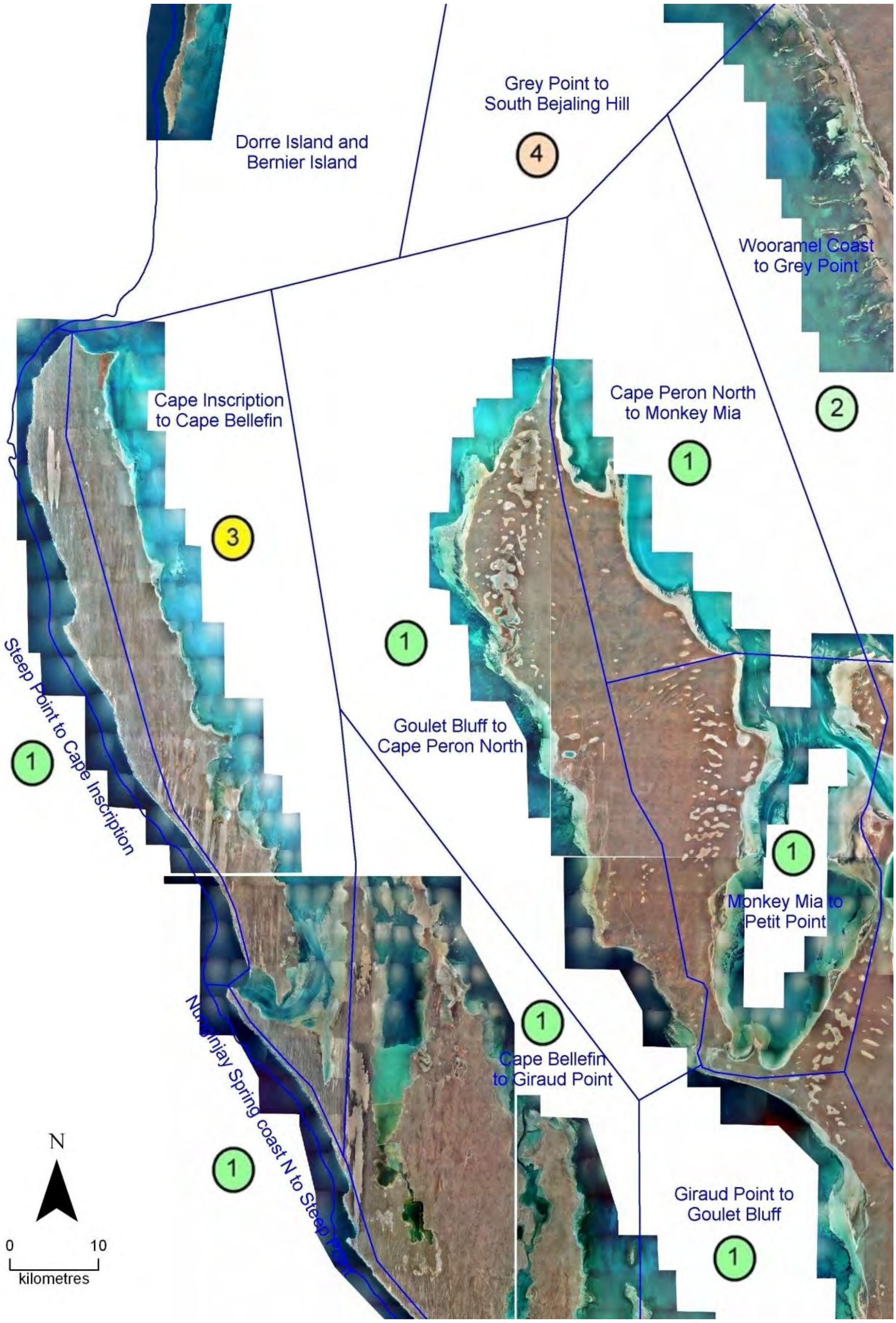

Figure C - 10: Vulnerability for Secondary Compartments for Western Shark Bay

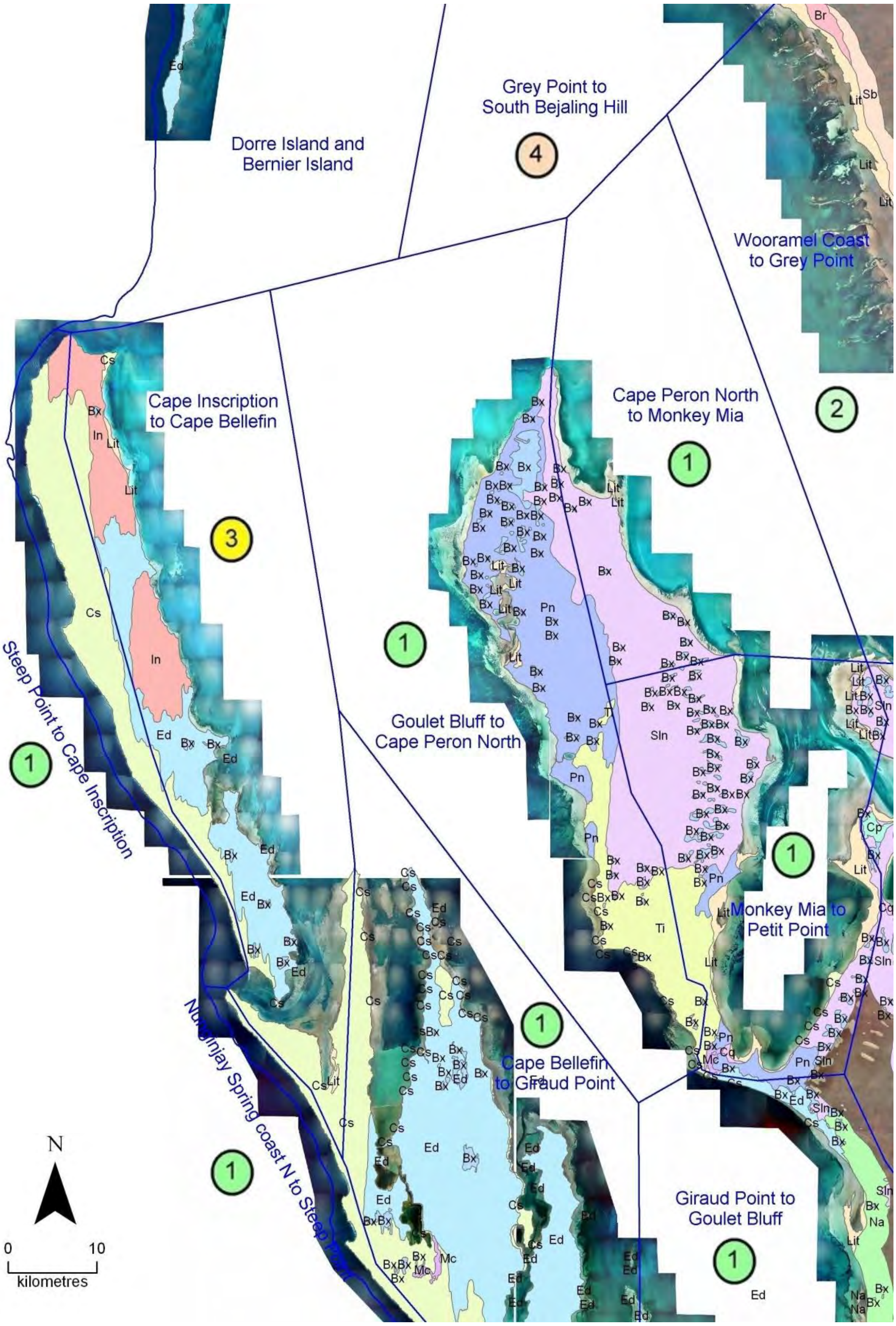

Figure C - 11: Land Systems for Secondary Compartments for Western Shark Bay

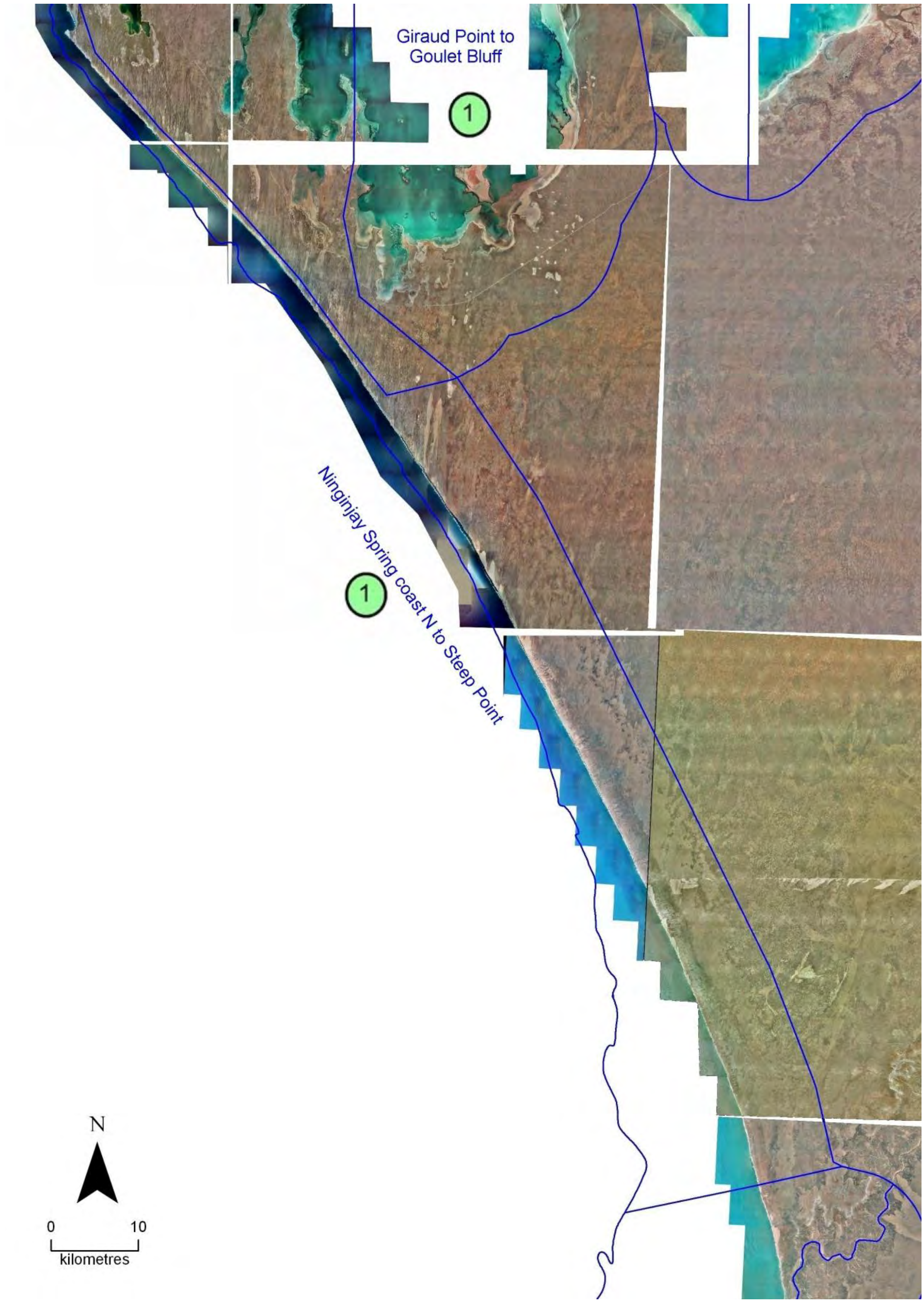

Figure C - 12: Vulnerability for Secondary Compartments for Southern Shark Bay and Nunginjay Springs coast N to Steep Point

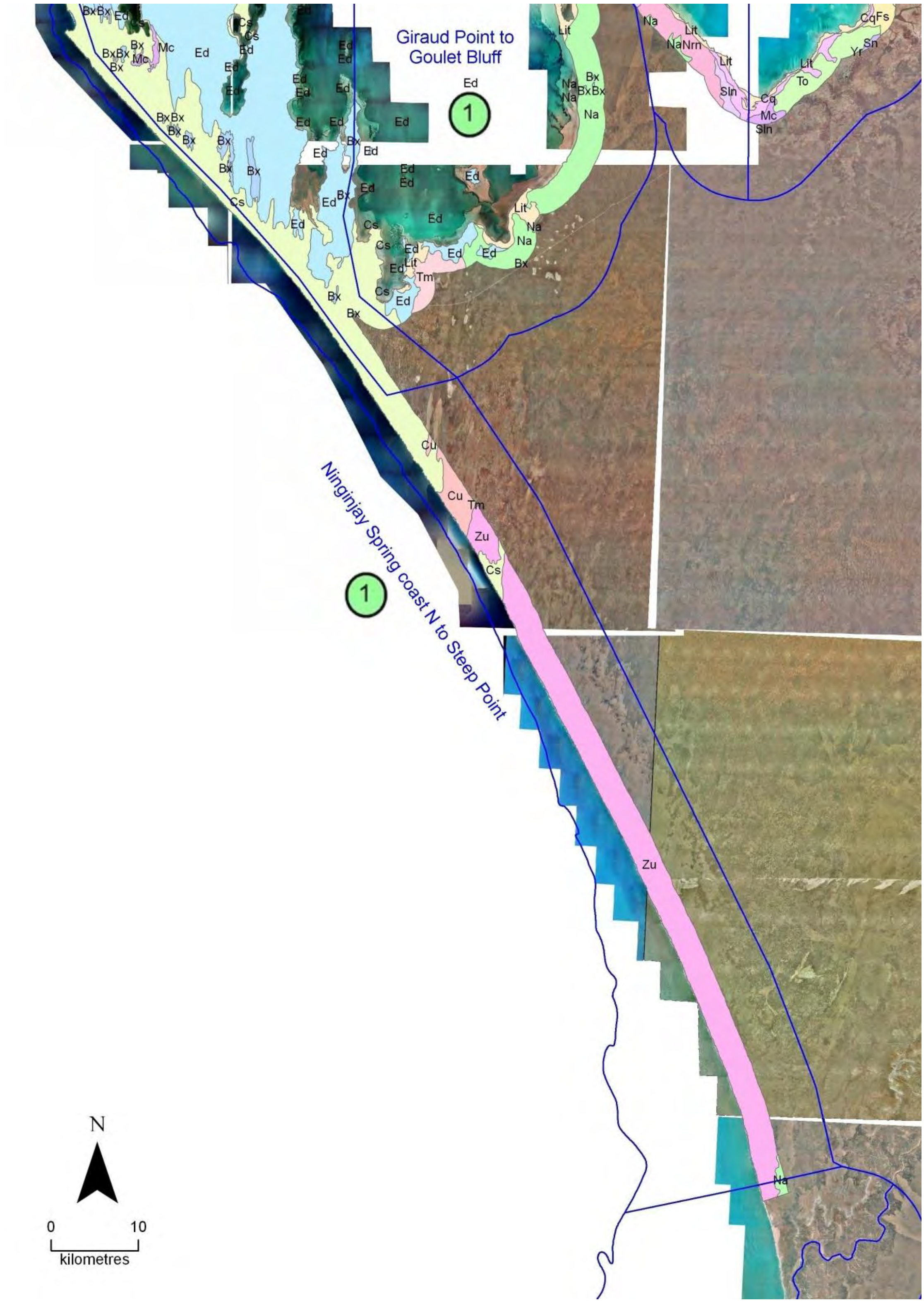

Figure C - 13: Land Systems for Secondary Compartments for Southern Shark Bay and Nunginjay Springs coast N to Steep Point

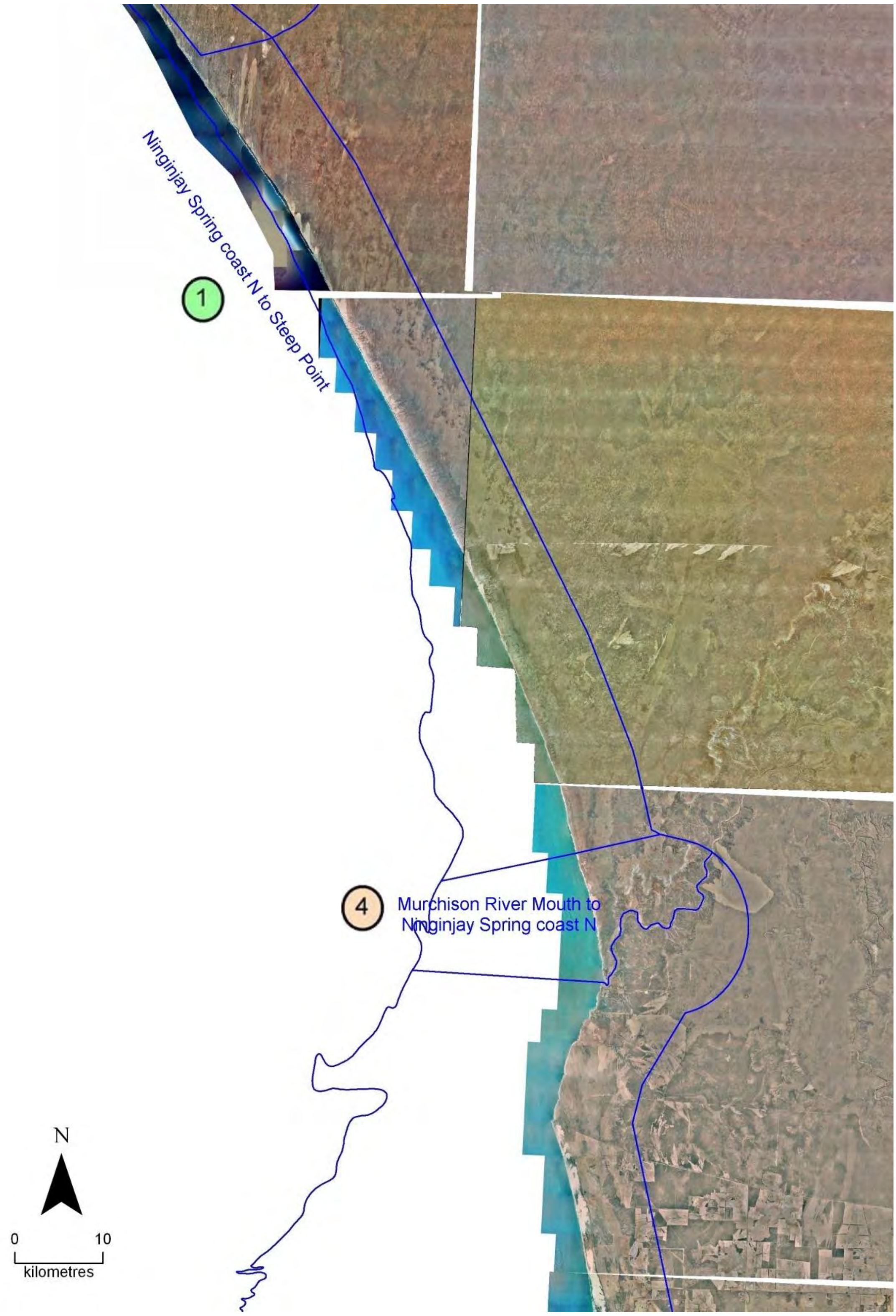

Figure C - 14: Vulnerability for Secondary Compartments for Murchison River Mouth to north of Nunginjay Springs coast N

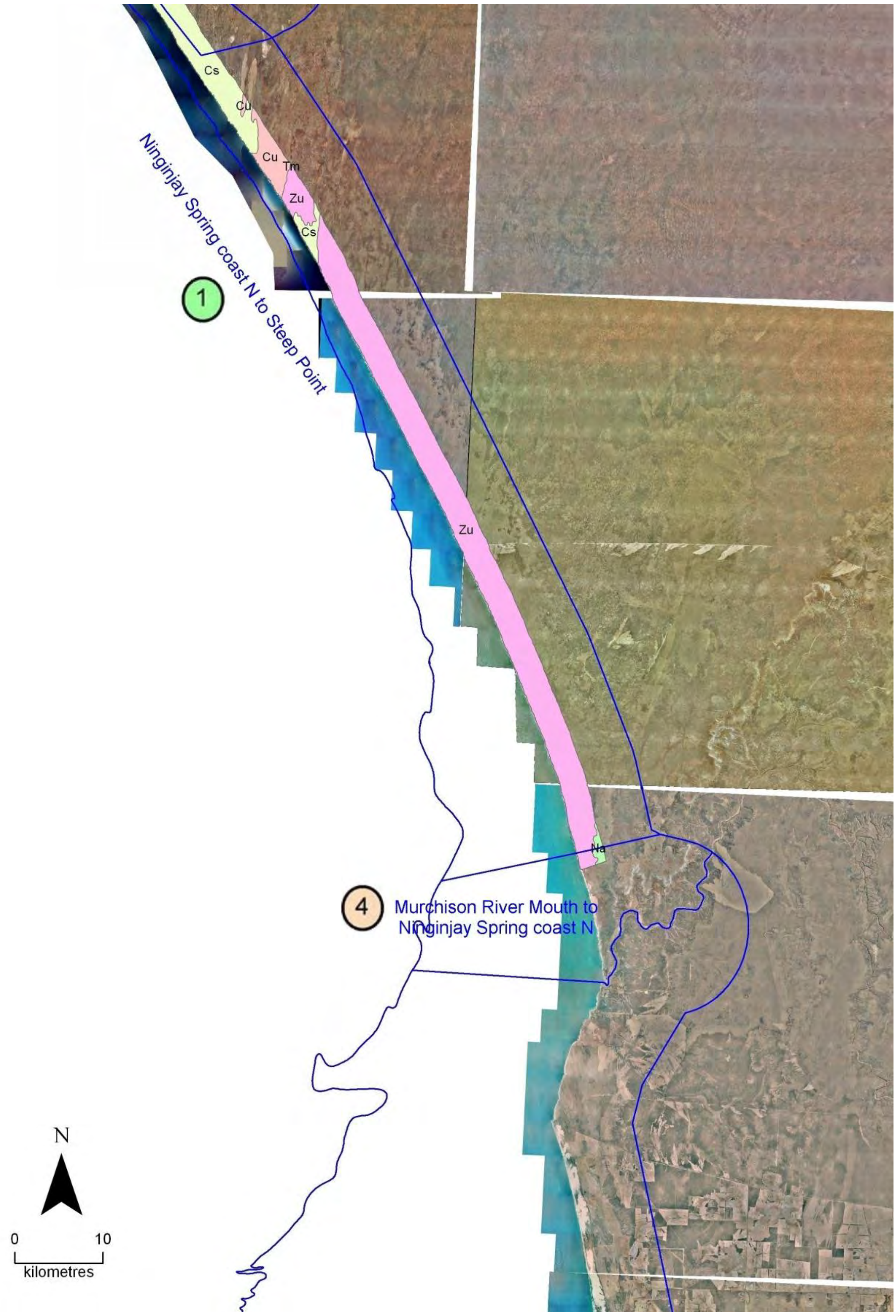

Figure C - 15: Land Systems for Secondary Compartments for Murchison River Mouth to north of Nunginjay Springs coast N

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Appendix D Definitions of Land Systems of the Shires of Shark Bay to Exmouth

The descriptions of land systems herein are taken directly from Payne *et al.* (1987, 1988) with additions and modifications.

Birrida Land System (Bx)

Low-lying evaporative pans of gypsiferous sediments, supporting low shrublands of samphire and saltbush.
Geology: Pleistocene deposits of gypsum, clay, silt and sand.
Geomorphology: Discrete platforms with raised centres, often elliptical or oval and occupying wide interdunal depressions; some receive influxes of seawater along channels connecting with the ocean but most show no surface drainage features beyond peripheral moat-like seepages.
Landforms: Gently sloping marginal zones, usually <200 m wide with flat to hummocky surfaces; soils are juvenile types of reddish brown sands over clays and sand, calcareous throughout with a mantle of calcareous gravel.
Hummocky platforms up to 3 m above central depression occur as banks or dune-like accretions; soils are juvenile types, generally thin layers of reddish brown sand over gypsiferous deposits.
Central depression is virtually flat; soils are gypsiferous deposits or juvenile types of red or reddish brown sandy clays overlying sands.
The height of the platform if believed to correspond to water levels in the Late Pleistocene. The moat surrounding the platform was formed when fresh groundwater seeped from the platform and dissolved the gypsum around its edge.

Brown Land System (Br)

Sandy plains with sparse longitudinal dunes, supporting tall shrublands of acacias.
Geology: Quaternary eolian quartz sand and foredunes, locally calcareous.
Geomorphology: Depositional surfaces of flat to gently undulating sandplains with longitudinal dunes and swales; no drainage features.
Landforms: Longitudinal dunes are linear ridges, mostly single, orientated north-south and up to 15 m in relief; soils are red sands.
Sandy plains often have undulating surfaces and locally are lightly mantled with limestone gravel; slopes are generally < 0.5%; soils are yellowish red to dark red sands with clay content increasing with depth; below about 1 m there are pebbles of limestone and shells.

Cardabia Land System (Ca)

Undulating sandy plains with linear dunes, minor limestone plains and low rises supporting mainly soft spinifex hummock grasslands with scattered acacias and other shrubs.
Geology: Quaternary eolian sand and calcarenite with Neogene calcrete duricrusts.
Geomorphology: Mainly depositional surfaces of undulating sandplains with some parabolic and longitudinal dunes and irregular calcrete outcrops and rises; no drainage features; broad-scale relief up to 70 m.

Landforms: Longitudinal dunes are linear or reticulate ridges, with a relief of 10-15 m; soils are red to dark red sands, loamy sands or non-coherent sand, usually >1 m in thickness, with or without calcareous accretions.
Sandy plains have undulating surfaces with slopes <4%; soils are red to brown sands, non-coherent sands to loamy sands usually >1 m deep and can be calcareous or non-calcareous throughout.
Irregular limestone ridges and rises with surfaces sparsely to densely mantled with limestone pebbles and cobbles; slopes mostly >4.5%; soils are dark reddish brown to yellow sands and sandy loams and calcareous throughout.
Small areas of undulating plains have shallow sandy soils over calcrete with occasional small stony outcrops; soils are reddish brown sands with paler subsoils to >1 m depth.

Chargoo Land System (Cg)

Flat, saline, alluvial plains subject to temporary inundation, characterised by numerous drainage depressions, low shrublands of saltbush and bluebush and tussock grasslands.
Geology: Quaternary clays, alluvium and eolian sand.
Geomorphology: Depositional surfaces forming low-lying alluvial areas within riverine floodplains, featuring gilgai plains, drainage foci and disorganised flow; relief to 1 m.
Landforms: Occasional low sandy rises; soils are eolian sands over wash deposits.
Weakly gilgaied or flat alluvial plains; slopes <0.2%; soils are brown to greyish brown clays, light to medium or medium over sandy or heavy clays; >1 m in depth.
Low-lying plains with gilgaied surfaces of <1 m relief as anastomosing tracts within the alluvial plains; soils are dark reddish grey or reddish brown medium to heavy clays; >1 m in depth.
Discrete to interconnecting drainage foci with clay soils, often gilgaied; soils are brown heavy clays >1 m in depth.
Narrow unchannelled drainage zones; soils are brown clays.

Claypan Land Unit (Cp)

Low-lying evaporative pans of clayey sediments supporting low shrublands of samphire and saltbush.
Geology: Holocene clays, silts and sands.
Geomorphology: Discrete flat depressions, often circular or elliptical, occupying interdunal depressions.

Coquina Land System (Cq)

Mostly unvegetated ridges of shell grit backed by coastal dunes supporting scattered tall acacia shrublands.
Geology: Holocene coquina – supratidal deposits of shells from the bivalve mollusc *Fragum erugatum* and low dunes of calcareous sand and gravel.
Geomorphology: Storm ridges formed during the Bibra Marine phase of the final Pleistocene interglacial transgression, with older calcreted benches and ridges; mostly <1 km wide with relief <8 m; no organised drainage features.
Landforms: Loose to indurated and calcreted supra-tidal ridges of coquina shell deposits up to 8 m above the tidal mudflats.

Undulating ridges and low dunes inland of the supra-tidal ridges; soils are shallow greyish brown sands with a high content of shell fragments and carbonate concretions.
Tidal mudflats.

Coast Land System (Cs)

Well developed coastal dunes with narrow swales, limestone plains, wave-cut platforms and beaches, supporting diverse tall and low shrublands.
Geology: Quaternary dune and beach deposits of unconsolidated or poorly consolidated quartz sand to quartzose lime sands over Quaternary eolianite and Neogene limestones.
Geomorphology: Coastal dunes, mainly long-walled parabolic and swales, stable when densely vegetated and undisturbed but highly susceptible to wind erosion which results in extensive northward developing blowouts whenever foredunes or crests become degraded; no drainage features.
Landforms: Long-walled parabolic dunes, relief mainly 30-60 m above swales; soils are non-coherent sands, light brown, light reddish brown or pink; >1 m deep with or without a mantle of limestone gravel; calcareous nodule throughout.
Interdunal swales and corridors with undulating sandy floors; soils are brown or reddish brown sands >1 m deep, mainly calcareous.
Steeply undulating foredunes; soils are pink or light brown loose sands >1 m deep.
Blowouts of loose sand up to 23 km long and 30 m deep with arcuate crests and steep north-facing slopes with bare deflation basins behind on exposed limestone.
Narrow plains or gently undulating surfaces of duricrusted calcrete often heavily mantled with boulders; soils are shallow alkaline sands.
Beaches and wave-cut platforms under storm and tidal influence.

Cullawara Land System (Cu)

Undulating rocky plains above the central sector of the Zuytdorp Cliffs supporting sparse low shrublands of saltbush with patches of tall *Acacia* and *Melaleuca* species.
Geology: Quaternary Tamala Limestone.
Geomorphology: Erosional surfaces with extensively rock-mantled plains, rises and low hills to nearly 300 m above sea level; mainly unchannelled drainage into small foci and depressions, or springs on sea cliff faces.
Landforms: Elevated rocky plains, slopes and low hills of Tamala Limestone up to 300 m above sea level; soils are skeletal pockets of sands and loams.
Undulating elevated plains, often densely boulder-mantled, up to 200 m above sea level; soils are shallow dark reddish brown fine sandy loams with limestone and calcareous concretions.
Restricted plains, nearly flat; soils are calcareous sands and sandy loams.
Boulder-mantled steep slopes, terraces and cliffs to 200 m above sea level.

Delta Land System (De)

Floodplains of the major rivers, supporting low shrublands of bluebush and saltbush, widely degraded and eroded.
Geology: Quaternary clay, silt, sand and gravel.
Geomorphology: Depositional surfaces of flat alluvial plains with undulating surfaces, locally accentuated by erosional redistribution of soils. Major floodplains exhibit irregular

channelled drainage and are flanked by slightly higher areas of alluvium overlain by broad, low sandy banks up to 7 m relief.
Landforms: Broad, sandy-surfaced banks of relief <1 m; soils are reddish brown sands to fine sandy loam, grading with depth to sandy clay loams >1 m deep.
Flat alluvial plains with slopes to 0.7%; soils are reddish brown, red or yellowish red duplexes or juvenile coarse loamy sands over sandy clays.
Flat floodplains with slopes to 0.4%; soils are reddish brown sand or loamy sand over sandy clay loams and sandy clays.
Isolated claypans with flat, bare surfaces.
Occasional flat plains with hummocky surfaces; soils are yellowish red calcareous duplexes and sandy loams over sandy clays.
Ephemeral swamps and drainage depressions with gilgaied surfaces; soils are reddish brown or reddish grey clays.
Levee backplains adjacent to major watercourses; soils vary in relation to scour lines and depositional hummocks: red, reddish brown or yellowish red sands or clays over silty or sandy clays.

Donovan Land System (Dn)

Gently sloping outwash plains and minor stony plains with alkaline loamy and clayey soils supporting tall shrublands of snakewood and other *Acacia* species.
Geology: Quaternary alluvium and colluvium with minor Tertiary limestones (Trealla Limestone and Giralia Calcarenite).
Geomorphology: Depositional surfaces receiving run-on from limestone hills of the adjacent land systems; broad, gently sloping outwash plains and alluvial fans with unchannelled or channelled drainage traces receiving more concentrated flow.
Landforms: Stony, gently sloping limestone plains with a light to moderate mantle of pebble-sized rock fragments and occasional areas of dissection; soils are dark red to red gradational loams or clays, calcareous throughout.
Calcrete rises and platforms with undulating surfaces and gravelly mantles; relief up to 5 m; soils are shallow red sandy loams, calcareous throughout.
Gently undulating plains and interfluves; relief up to 8 m; soils are reddish brown clay loams to clays, calcareous throughout.
Lower outwash plains and fans with lightly gravel-mantled or slightly mounded surfaces receiving sheet flow; soils are reddish brown alkaline loams or clays with or without calcareous inclusions.
Channelled drainage tracts with little or no surface mantling; soils are reddish brown duplex or clay types.

Dune Land System (Dun)

Dune fields with soft spinifex and minor hard spinifex grasslands in coastal areas.
Geology: Quaternary eolian sands.
Geomorphology: Dune fields with no organised drainage; dunes trending approximately north-south and frequently becoming reticulate; narrow swales with minor areas of claypans and swamps; relief up to 15 m.
Landforms: Linear and reticulate dunes up to 15 high and 2.5 km long 100 to 200 m apart becoming reticulate with hummocky crests; soils are dark red sands and loamy sands.

Swales comprising sandy surfaces 50 to 300 m wide between the dunes; soils are dark red sands and loamy sands.
Circular or oval, low-lying swamps and depressions between the dunes, up to 500 m in extent; soils are surface-cracking reddish brown clays.
Bare, circular or oval claypans less than 150 m in diameter; soils are dark red clay soils often with lime or gypsum in the profile.

Edel Land System (Ed)

Undulating sandy plains with occasional dunes, limestone ridges and saline flats supporting low acacia shrublands with some saltbush and heath communities.
Geology: Quaternary Tamala Limestone with minor areas of mixed supra-tidal deposits and calcareous sand.
Geomorphology: Undulating plains of eolian calcareous sands with minor longitudinal dunes, small areas of outcropping limestone and saline plains; no drainage features.
Landforms: Longitudinal dunes and dune-like sandy crests over limestone ridges; relief up to 15 m; soils are light reddish brown calcareous sands.
Restricted limestone plains and stony rises densely mantled with pebbles, cobbles and boulders; soils are red, reddish brown or yellowish brown shallow sand, loamy sand or clayey sands.
Swales and undulating plains sparsely to moderately mantled with limestone gravels; soils are yellowish red or reddish brown sands or loamy sands, calcareous throughout.
Low-lying saline plains, lightly to moderately mantled with limestone pebbles or cobbles; soils are very shallow grey loamy sands with calcareous inclusions.

Foscal Land System (Fs)

Calcrete mesas, buttes and dissected plateaux with stony slopes and broad, low plains supporting tall and low acacia shrublands with saltbush and bluebush.
Geology: Cretaceous limestone, Tertiary calcrete and Quaternary alluvium.
Geomorphology: Erosional and depositional surfaces of the dissected margins of the Carbla Plateau and isolated calcrete buttes with relief up to 40 m; short, steep slopes above extensive depositional plains with low intensity reticulate drainage.
Landforms: Flat to undulating tops of dissected mesas and plateaux; relief up to 50 m above lower units; sparse to moderate cobbles; soils occur as pockets of red or reddish brown sandy loam with calcareous inclusions and gypsiferous concretions.
Steep, concave upper slopes with a mantle of cobbles; shallower lower slopes sparsely mantled with pebbles; soils are light to dark red or reddish brown sandy clay loam to sandy clays with calcareous inclusions and gypsiferous concretions.
Low, stony rises up to 10 m relief with sparse pebble mantle; soils as pockets of shallow calcareous red sandy loams with calcrete concretions and pebbles.
Low, nearly flat to undulating plains, sparsely mantled with limestone or calcrete gravels; soils are red or dark red sandy-surfaced duplexes with calcareous inclusions and gypsiferous concretions.
Channelled or unchannelled flow zones, mostly narrow but some up to 400 m wide; soils are dark reddish brown gradational sandy clay loams to sandy clays with inclusions and concretions of calcrete and limestone.
Restricted, low-lying, almost flat saline plains; soils are red duplexes.

Inscription Land System (In)

Gently undulating sandy plains on Dirk Hartog Island with limestone at shallow depth, bounded by sea cliffs and narrow beaches supporting heath vegetation with patches of tall acacia shrubs.
Geology: Quaternary limestones
Geomorphology: Gently undulating limestone plains with thin sand cover, minor limestone plains, sea cliffs and wave-cut platforms; relief mostly <20 m but cliffs up to 40 m above sea level.
Landforms: Gently undulating plains with thin sand cover overlying calcrete or limestone; soils are reddish brown sands or sandy loams with calcareous inclusions throughout.
Very restricted stony plains with outcrops of limestone, usually <200 m in width, mantled with limestone fragments; soils are shallow reddish brown sands over limestone.
Limestone cliffs up to 40 m above sea level; bare limestone platforms and sandy beaches.

Jubilee Land System (Ju)

Limestone hills and stony plains supporting mainly hard and soft spinifex hummocky grasslands with scattered acacia shrubs.
Geology: Cretaceous and Tertiary marine limestones.
Geomorphology: Hills and low cuestas with short, stony footslopes; extensive undulating stony plains above lower, flatter plains; sub-parallel drainage patterns.
Landforms: Dissected low hills and cuestas with nearly flat to rounded crests and densely mantled slopes; strike-aligned cuestas are up to 5 km long with slightly benched slopes and dense mantles of rock fragments.
Undulating stony plains and slopes variably mantled with limestone fragments; soils are reddish brown loams to silty clay loams.
Nearly flat lower plains lightly mantled with limestone fragments; soils are dark reddish brown loams grading to clay loams with calcareous inclusions.
Upper streams incised up to 5 m into limestone draining into sub-parallel floors of low intensity up to 100 m wide more or less channelled; soils are reddish brown clay loams to light clays.

Learmonth Land System (Le)

Sandy outwash plain marginal to the Cape Range supporting soft spinifex hummocky grasslands with scattered acacia shrubs.
Geology: Tertiary Trealla Limestone and Quaternary calcarenite, colluvium, alluvium and eolian sand.
Geomorphology: Pediment-like footslopes and lower depositional colluvial plains with mainly sandy surfaces, dissected by parallel low density drainages, ending in fan-shaped outwash plains fringed by coastal dunes and beaches.
Landforms: Gentle stony footslopes below Cape Range up to 42 m above lower units; soils are shallow sandy clays grading to medium clays lightly to moderately mantled with limestone gravels and with limestone inclusions throughout.
Outwash plains lightly mantled with limestone gravels; soils are dark reddish brown gradational calcareous loams
Sandy plains, occasionally undulating; soils are red to reddish brown sand or loamy sand with calcareous inclusions throughout.

Low hind dunes; soils are calcareous sands.
Low lying restricted plains with loamy sands inland of hind dunes.
Dendritic to parallel incised channelled drainage carrying bedloads of pebbles and cobbles.
Sandy beaches and foredunes in low energy environments of Exmouth Gulf.

Littoral Land System (Lit)

Coastal foredunes, samphire flats and bare mudflats, sandy islets and mangrove fringes.
Geology: Quaternary tidal flat deposits, mostly mud and sand.
Geomorphology: Supratidal depositional plains of low relief, mainly as bare or samphire-covered mudflats, sandy beaches and islets below a low foredune of shelly sand
Landforms: Longitudinal dunes up to 10 m high; soils are shelly sands.
Samphire-covered flats with silty loam and silty clay soils often intergrading with mudflats.
Supratidal mudflats up to 500 m wide, infrequently inundated, of shelly limesand, silt and clay.
Mangrove fringes with narrow depressions and tidal channels.

MacLeod Land System (Mc)

Broad, saline plains with sandy banks and low rises above saline slopes and bare mudflats; bare surfaces of low shrublands of samphire and saltbush.
Geology: Quaternary saline lake beds and gypsiferous sand dunes over fossil coral reefs with outcrop locally.
Geomorphology: Flat depositional plains with banks and rises up to 10 m relief draining onto mudflats or playa lake beds via fringing clay plains with poorly developed parallel incisions.
Landforms: Sandy banks, rises and lakebed islands with undulating surfaces and relief up to 10 m; soils are brown sandy loams to sandy clay loams or gypsiferous juvenile types.
Flat, saline plains; soils are highly saline and gypsiferous juvenile types, brown to yellow loams or sands.
Dissected slopes with irregular surfaces and parallel drainage incisions; soils are yellowish red to reddish brown light medium clays to sandy clay.
Mudflats, lime silts and sands with gypsum and salt deposits.

Mallee Land System (Ml)

Coastal dunes and sandy plains with limestone outcrops supporting mallee eucalypts and hard spinifex.
Geology: Quaternary eolian sand and calcarenite and Neogene Trealla Limestone.
Geomorphology: Longitudinal dunes with broad swales with sandy surfaces over limestone that outcrops as restricted plains near Lake MacLeod.
Landforms: Longitudinal dunes, mostly linear, 7-15 m high and 1-5 km long; soils are red to dark red unconsolidated sands.
Plains of outcropping limestone and thin calcareous soils, mostly occurring interdunally.
Swales and sandy plains with undulating surfaces with or without a very sparse mantle of limestone gravel; soils are dark red to dusky red sandy or loamy sand.
Plains with thin calcareous soils, locally calcreted and gravelly, fringing Lake MacLeod.

Nanga Land System (Na)

Undulating plains of eolian sand supporting shrub heath and tree heath dominated by proteaceous and myrtaceous species.
Geology: Quaternary eolian sand.
Geomorphology: Undulating sandplains with occasional ridges, locally with longitudinal dunes; no drainage features.
Landforms: Plains, undulating or strongly undulating relief up to 50 m; confused reticulate sand ridges 10-15 m above the plains; soils are non-coherent red sands, mostly non-calcareous except near the coast when calcareous inclusions are found.

Nerren Land System (Nrn)

Sandplains with scattered or clumped mallee and tree-form eucalypts over wanyu-dominated tall shrublands.
Geology: Quaternary eolian sand.
Geomorphology: Gently sloping or undulating surfaces up to 20 m relief; no drainage development.
Landforms: Extensive flat or gently undulating broad sandy plains with relief up to 20 m; soils are non-coherent dark red, red or yellowish red sand or loamy sand.
Restricted flat or gently undulating plains very sparsely mantled with calcrete gravels; soils are red or reddish brown gradational loams or sands with calcrete inclusions and calcareous concretions throughout.

Peron Land System (Pn)

Undulating plains of calcareous sand supporting low acacia shrublands and *Lamarchia hakeifolia* heaths.
Geology: Quaternary eolian sands with minor areas of birrida gypsiferous deposits.
Geomorphology: Undulating sandy plains and low coastal dunes; no organised drainage features.
Landforms: Undulating sandplains; soils are red or reddish brown sands, sometimes calcareous, locally with clayey sand below 60 cm.
Elliptical or rounded small birridas; soils are highly gypsiferous juvenile types.
Low coastal dunes and banks.

Range Land System (Ra)

Dissected limestone plateaux, hills and ridges with gorges and steep stony slopes supporting hard spinifex, sparse shrubs and eucalypts.
Geology: Neogene Tulki and Trealla Limestones.
Geomorphology: Dissected anticlinal plateaux of 250-300 m relief with residual summits, hills and ridges with steep footslopes; high density dendritic drainage east and west of the range and locally internally into large depressions.
Landforms: Residual hills, summits and ridges of a plateau; soils are limited to pockets of calcareous loams.
Gorges and escarpments with steep and irregular slopes, often boulder-mantled; soils are skeletal or absent.
Upper and lower rock-mantled slopes; soils are dark red sandy calcareous loams in shallow pockets.

Intensely dendritic channels and creek lines, often deeply incised carrying bedloads of sand and gravel.
Internal drainage depressions draining portions of the dissected plateau, usually flat bottomed and rounded in shape.

River Land System (Rir)

Narrow, seasonally active floodplains and major channelled water courses supporting moderately tall shrublands or woodlands of acacias and fringing communities of coolibah and river gum.
Geology: Quaternary alluvium.
Geomorphology: Floodplains with minor channels; flow zones adjacent to major water courses; slightly higher sandy banks and narrow sandplains less regularly flooded; major channels; relief mainly 2-3 m .
Landforms: Floodplains with flat or undulating surfaces carrying channels and runnels directing flow both away from and returning to major water courses; soils are red or dark red sands, loams and light clays.
Raised sandy banks and marginal plains with hummocky surfaces, mostly <300 m wide and 1-2 m above adjacent areas; soils are red or dark red sands.
Major river beds and water courses 50-500 m wide, incised 4-10 m with steep banks, carrying bedloads of coarse sand; minor channels and meandering runnels incised and flanked by hummocky flood banks; soils are dark red sands and silty loams.

Sable Land System (Sb)

Nearly flat alluvial plains with occasional sandy rises, low shrublands of saltbush and Gascoyne saltbush and some tall acacia shrublands.
Geology: Quaternary deposits, mostly alluvial or colluvial clay, silt, sand or gravel, semi-consolidated when near river deltas; small areas of eolian sand.
Geomorphology: Extensive saline, alluvial plains with minor sand banks and sand sheets up to 3 m above the surrounding plains; minor drainage foci; ephemeral swamps and highly saline flats; no organised external drainage.
Landforms: Sand banks up to 2 m and sand sheets up to 4 m relative relief; soils are dark red sands or sandy loams.
Flat to very gently undulating alluvial plains; soils are red to dark reddish brown duplexes, loamy sand over clay/loam or clays with inclusions of calcrete, gypsum or limestone.
Flat to concave interbanks between sandy banks; soils are dark reddish brown duplexes, loamy sands over fine sandy clay with calcrete inclusions.
Seasonally inundated elliptical drainage foci; soils are reddish brown sandy loams lightly mantled with ironstone gravel.
Seasonally inundated shallow elliptical swamps; soils are clays.
Small, shallow claypans.
Low-lying flat saline plains mainly near the coast; soils are dark red or red duplex sands over sandy clays with inclusions of limestone and calcareous concretions or gypsum.

Sandplain Land System (Sln)

Extensive red sandplains with tall shrublands of wanyu and under-story shrubs or low woodlands of sandplain gidgee.

Geology: Quaternary eolian sand.
Geomorphology: Flat to gently undulating extensive sand sheets, generally without dune development; drainage features absent; broad-scale relief up to 50 m.
Landforms: Occasional low longitudinal dunes up to 10 m high; soils are dark red sands.
Flat or gently undulating broad sandy plains, often extensive and rather uniform; relief up to 42 m; soils are dark red or dusky red sand, loamy sand or clayey sand.
Small to medium-sized drainage depressions; soils are red gradational loams.

Snakewood Land System (Sn)

Plains with red duplex soils supporting tall shrublands of snakewood with an understory of silver saltbush.
Geology: Quaternary sandplain and minor outcrops of Tertiary calcrete.
Geomorphology: Flat plains with sandy surfaces and minor calcrete plains; no drainage features.
Landforms: Undulating stony limestone plains with outcrops of calcrete and limestone mantled with limestone pebbles and cobbles; relief up to 5 m; soils are shallow gradational types with calcareous inclusions.
Flat to slightly undulating sandy banks and sand sheets; soils are red sands.
Flat plains with gradational soils overlying limestone and very lightly mantled with calcrete gravels; soils are reddish brown gradational types, sandy clay loam to fine sandy clay with calcrete inclusions and carbonate concretions.
Flat plains with an undulating surface lightly mantled with calcrete gravels; soils are red to dark red duplex, sand to sandy loam over sandy clay loam to sandy clay with carbonate concretions.

Taillefer Land System (Ti)

Plains of calcareous sand, minor limestone ridges, low coastal dunes and sea cliffs.
Geology: Quaternary sandplain and beach dune deposits with minor outcrops of Tamala Limestone.
Geomorphology: Undulating coastal sandplains with isolated rocky ridges; low longitudinal dunes near the ocean; occasional birridas, otherwise no drainage features.
Landforms: Rocky limestone ridges and outcrops, relief up to 60 m, slopes densely mantled with limestone pebbles or cobbles; soils are reddish brown loamy sands with limestone inclusions.
Flat to undulating plains of calcareous sand, relief up to 55 m; soils are reddish brown to yellowish red sand or loamy sands, lightly mantled with calcrete gravels and with limestone inclusions throughout.
Low coastal dunes, mostly short-walled and parabolic; soils are reddish yellow sands.
Low-lying plains with undulating surfaces; soils are red sand or loamy sand with limestone inclusions throughout.
Elliptical or rounded birridas <500 m long with nearly flat surfaces; soils are highly gypsiferous juvenile types.

Tamala Land System (Tm)

Plains with a thin covering of sand over limestone interspersed with stony rises; former saltbush and acacia shrublands, widely degraded and now replaced by winter pastures of exotic annuals.

Geology: Quaternary Tamala Limestone.

Geomorphology: Boulder-mantled limestone plains and rises interspersed with sandy-surfaced plains and sand sheets; much local redistribution of topsoil material through wind erosion; no drainage features.

Landforms: Rounded limestone rises, mostly 10-40 m above surrounding plains, lightly to heavily mantled with limestone cobbles and boulders; soils are shallow reddish brown, reddish yellow or grey loams, calcareous throughout, with or without windblown surface deposits of sand.

Undulating sandy-surfaced plains lightly mantled with calcrete gravels; soils are weak red or reddish brown sands with limestone inclusions throughout.

Gently undulating, very stony limestone plains, heavily mantled with limestone boulders; soils are weak red or reddish brown sands with limestone inclusions throughout.

Undulating plains of calcareous sand; soils are reddish brown sands with limestone inclusions throughout.

Restricted flat of undulating saline plains with saline or gypsiferous soils.

Toolonga Land System (To)

Gently undulating plains of calcrete outcrops with local and internal drainage supporting tall acacia shrubland.

Geology: Tertiary calcrete with an authigenic limestone duricrust and Quaternary colluvial deposits.

Geomorphology: Extensive undulating calcrete plains of low relief (up to 10 m); minor areas of sandplain; plains with ferruginised surface material; drainage foci and saline plains.

Landforms: Undulating stony limestone plains with outcrops of calcrete and limestone, moderately or densely mantled with limestone pebbles or cobbles.

Flat to gently undulating plains, some very sparsely mantled with calcareous gravel; soils are red or dark red duplex, sandy loam over sandy clay with calcareous concretions.

Gently undulating sandy plains and banks, mostly <1 km in extent; soils are dark red loamy sands.

Flat stony plains, densely mantled with ironstone or mixed gravel; soils are dark red or dusky red sandy clays.

Unchannelled flow zones up to 500 m wide and often ill-defined; some are very sparsely mantled with limestone gravel; soils are dusky red sandy clays.

Isolated low-lying areas with gilgaied surfaces subject to seasonal flooding; soils are reddish brown medium clays with ironstone, calcrete and other gravelly inclusions.

Flat saline plains, some sparsely mantled with calcrete pebbles or ironstone gravels; soils are reddish brown or yellowish red sandy surfaced duplexes with carbonate concretions.

Trealla Land System (Tr)

Elevated plains and marginal slopes with shallow soils over limestone, supporting moderately close tall acacia shrublands and minor areas of low shrublands of bluebush.

Geology: Miocene fossiliferous calcirudite and calcarenite.

Geomorphology: Gently sloping erosional plains mantled with limestone pebbles and stony outcrops with internal or disorganised drainage.
Landforms: Elevated stony limestone plains with up to 70 m relief with outcropping limestone and pebble mantle; soils are shallow reddish brown gradational calcareous loams to fine sandy clays.
Flat plains over limestone, very lightly mantled with limestone pebbles; soils are gradational red loams, fine sandy loams to fine sandy clay loams with limestone inclusions throughout.
Dissected slopes with channelled dendritic drainage, moderately to heavily mantled with limestone pebbles; soils are dark red calcareous loams.
Broad drainage depressions with flat micro-relief; soils are dark red gradational calcareous loams.

Warroora Land System (Wr)

Flat to gently sloping saline alluvial plains with minor areas of sand and limestone supporting tall acacia shrublands and low shrublands of saltbush, bluebush and samphire.
Geology: Quaternary calcrete, coquinite, alluvium and colluvium with minor eolian sand.
Geomorphology: Depositional surfaces of calcareous alluvium and colluvium, with minor areas of limestone outcrop and eolian sand, forming flat to gently sloping plains; drainage is internal into depressions and sluggish tracts; relief up to 4 m.
Landforms: Limestone outcrop plains with flat to undulating surfaces, sparsely to moderately mantled with limestone pebbles; soils are dark red or reddish brown fine sandy loam to sandy clay loam with calcareous inclusions throughout.
Low sandy banks with undulating surfaces with or without a sparse mantle of limestone gravel; soils are reddish brown, yellowish red or red sand and sandy loam with or without limestone and shell fragments.
Flat alluvial plains, higher parts locally with mantle of limestone gravel and cobbles; soils are duplex calcareous types, reddish brown or red loamy sands over sandy clays or sandy loams with limestone and shell fragments throughout.
Flat saline plains; soils are red duplex fine sandy loam over sandy clay loam to medium clays with shell fragments throughout.
Flat-bottomed ephemeral swamps and drainage depressions of irregular size and shape; soils are reddish brown clay loams or clays.

Yaringa Land System (Yr)

Sandy plains with poorly developed dunes and restricted interbank plains supporting tall shrublands of wanyu and other acacias.
Geology: Quaternary eolian sandplain and Tertiary calcrete duricrusts on Cretaceous Toolonga Calcilutite.
Geomorphology: Plains of shallow red sands overlying calcrete and limestone with weak longitudinal dune development in some areas; drainage features limited to scattered depressions.
Landforms: Longitudinal dunes, 5-12 m high; soils are dark red non-coherent sands.
Slightly undulating sandplains and sandy banks; soils are dusky red to dark red loamy sands, not calcareous, but overlying calcrete.
Flat gravel plains between sandy banks or low dunes, moderately mantled with mixed gravels; soils are shallow loam to dark red loams or clays with carbonate concretions.

Small, flat-bottomed drainage depressions with clay soils.

Zuytdorp Land System (Zu)

Elevated plains and low hills near the Zuytdorp coastline supporting low heath, mallee shrublands and paper bark thickets.
Geology: Quaternary Tamala Limestone.
Geomorphology: Very steep stony slopes and cliffs rising from sea level to an elevated plateau at 200 m above sea level, continuing inland as limestone plains and low, rounded hills mantled by limestone fragments; no drainage features.
Landforms: Undulating and low stony hills, lightly to moderately mantled with limestone cobbles; soils are shallow, very dark grey fine sandy loam, with limestone inclusions and calcareous concretions.
Elevated stony limestone plains with patches of thin sand cover or stony outcrops, lightly mantled with limestone cobbles and boulders; soils are very shallow brown sands with limestone inclusions.
Elevated, gently undulating sandy plains; soils are yellow or brown sands.
Steep seaward slopes and cliffs with limestone boulders and thin sandy soils above sea cliffs, relief mainly about 200 m.

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Appendix E Secondary Compartment Descriptions

All location names within this table are based on the three sources listed in Section 6.

SECONDARY COMPART.	INSHORE	SHORE	BACKSHORE
Giralia to Locker Point	Between Giralia and Locker Point the coast faces WNW into the shallow waters of Exmouth Gulf. The 10m isobath is between 10 and 18km offshore. It shelves gently with a wide sub-tidal terrace crossed by numerous tidal creeks.	The irregular shore is comprised of a broad complex system of tidal channels and flats.	Barrier development in this compartment is limited to chenier spits and a mobile sand sheet close to Turbridgi Point and in the vicinity of Locker Point. Further south the coast is comprised of bare slat flats between 5 and 11km wide. These include algal zones; patches of halophytic vegetation; residual mounds of older sediments, some of which are lithified; and tidal creeks along the seaward margin.
Learmonth to Giralia	South of Learmonth the coast faces NE into shallow water at the head of the gulf. The inshore waters, those within 10km of the shore, are less than 10m deep and shelve gently from the central channel of the gulf to a sub-tidal rock pavement along the shore.	A broad complex system of tidal channels and flats, with some backing onto low cliffs and sand ridges, occurs along the deeply indented and irregular coast south of Learmonth. Major tidal creek channels and extensive tidal flats extend over 5km into the embayments. Complex relict sandy and gravel beaches are apparent as spits, cheniers and beach ridges on the headlands and along rocky sections of shore.	Vegetation cover on the spits, cheniers and dune ridges is highly variable along the coast. Where there are barrier dunes the foredune vegetation cover is between 25 and 50% whereas the barrier supports a higher cover of 50 to 75%. The tidal flats appear to have broad salt flats with well developed tidal creeks.
North West Cape to Learmonth	The compartment identifies the northern sector of coast facing eastward into Exmouth Gulf. The gulf is 40km wide at its mouth and extends approximately 80 km along its SSW to NNE axis. The waters of the Gulf are over 20m deep. The bathymetry rises more rapidly to the western shore than to the wide sub-tidal terrace and intertidal flats of the eastern shore. A rocky sub-tidal terrace, approximately 500m wide, skirts the shore of the Exmouth coast between the North West Cape and Pebble Beach.	The ESE facing shore has a straight section between Pebble Beach and the Exmouth Marina; a shallow enbayment extends from the marina to Bundegi; and a large cuspate foreland peaks at Point Murat between Bundegi and North West Cape. The beaches along the northern flank of the cuspate foreland are perched on a supratidal rock platform. Some are storm deposited boulder beaches. Beaches south of Point Murat are also perched, in the northern section on beachrock but further south on rock platforms closer to high water level. Mixed sand and pebble beaches are common features along this part of the coast.	A moderately high (10 to 15m) dune ridge comprised of nested blowouts encloses low, supratidal flats on the cuspate foreland. A small proportion of the blowouts are active, particularly those in the vicinity of Bundegi. The overall vegetation cover on the foredunes and frontal dune ridge is between 50 and 75%. The dune ridge narrows with distance south against a pattern of nett northerly littoral drift. The ridge abuts and overlays older colluvial sediments. There is considerable ORV tracking along the backshore close to the junction of the dunes with rock platforms on parts of the coast and this inhibits foredune stability.

SECONDARY COMPART.	INSHORE	SHORE	BACKSHORE
Winderabandi Point to North West Cape	The inner continental shelf is deep and steep close to shore. It rises to a fringing coral reef, lithified reef platform and shallow lagoons within 2km from the shore. In the lagoons, sandy sediments overlie a rocky pavement.	The predominantly WNW facing shoreline is irregular in form. Sheltered sandy beaches are commonly perched on intertidal platforms, inshore pavement and beach rock ramps. Additionally some, such as the beach at Turquoise Bay, are on the flanks of small salients and cuspate forelands. Beach profiles vary in form from flat to rounded on the sheltered reaches of coast. Small, ephemeral streams are also common along the coast.	A narrow episodic transgressive barrier is present in the compartment. It is mainly narrow but widens along the NW facing coast between Jurabi Point and North West Cape. The foredunes are partly scarped. Blowouts are present in some places although the vegetation cover on the barriers varies between 50 and 75% and is higher in places.
Point Cloates to Winderabandi Point	The inner continental shelf is deep and steep close to shore. It rises to a fringing coral reef, lithified reef platform and shallow lagoons within 6km from the shore. The reef changes orientation from a SW to NW aspect in the centre of the compartment.	The shape of the shore is controlled by the offshore reefs and, as a result, the shoreline tends to be rhythmic in shape. Four large cuspate forelands have developed within their lee. A narrow sandy beach is continuous along the shore. It has a moderately sheltered profile with a profile form varying between segmented and reflective depending on aspect and the presence of beach rock outcrops.	The cuspate forelands carry a diverse range of dunal systems, including episodic transgressive dunes, beach ridge and foredune plains, blowouts and mobile sand sheets. Vegetation cover is similarly diverse, ranging up to >75% cover. There is evidence of ORV tracking on a tidal flat in the compartment.
Point Maud to Point Cloates	The inner continental shelf is deep and steep close to shore. It rises to a fringing coral reef, lithified reef platform and shallow lagoons within 6km from the shore. The lagoons vary in width up to approximately 4km, with the discontinuous coral reef closing the mouth of a large arcuate embayment.	Rock outcrops break the arcuate shoreline into smaller, shallow, W facing embayments. This gives an irregular structure to the shoreline. The beaches are sheltered, have segmented to reflective profiles and are commonly perched on beach rock or rock platforms.	The southernmost of the small embayments adjoins Point Maud and faces WNW. It contains a foredune plain terminating to the north in a series of parabolic dunes. In contrast to this the northernmost embayment, immediately south of Point Cloates has an episodic transgressive barrier with mobile blowouts and sand sheets overlying older dune topography. Foredunes are discontinuous and scarped in place, and the barriers have an overall vegetation cover of 25 to 50%.
Alison Point to Point Maud	The inner continental shelf is deep and steep close to shore. It rises to a fringing coral reef, lithified reef platform and shallow lagoons within 2km from the shore.	Between Alison Point and Point Maud the W facing shore is protected by discontinuous coral reef and shallow coastal lagoons. The narrow, mainly perched beach is discontinuous and broken by rock outcrops; including beachrock, platforms and low cliffs. The beaches are sheltered and have a segmented to reflective morphology outside Coral Bay.	This is an area of sediment accumulation where perched episodic transgressive barriers have formed immediately south of Pelican Point and Point Anderson as well as on the cuspate foreland at Point Maud. In places the seaward margins of the barriers have been truncated and infilled with narrow, localised foredune plains. The foredunes are discontinuous and have a vegetation 50 to 75% cover.

SECONDARY COMPART.	INSHORE	SHORE	BACKSHORE
Gnaraloo Bay to Alison Point	The inner continental shelf is deep and steep close to shore. It rises to a discontinuous fringing coral reef or lithified reef platform within 1-2km from the shore.	The shoreline has two components. Its southern half faces WSW and has a series of small cuspate forelands in the lee fringing reefs. The northern half has a more NW aspect and the fringing reef is not as shallow. The coast of this section forms a shallow embayment into which streams intermittently flow. A narrow, sheltered sandy beach is discontinuously perched on beachrock outcrops along the coast.	Barrier development is limited to small foredune plains on the cuspate forelands. Elsewhere narrow foredune ridges abut or overlie older Pleistocene dunes. The vegetation cover varies but is commonly between 50 and 75% on the foredunes and cuspate forelands.
Cape Cuvier to Gnaraloo Bay	The inner continental shelf is deep and steep close to shore. South of Red Bluff the inshore commonly grades steeply to a narrow rock platform and cliffed coast. Ningaloo Reef, a fringing coral reef, is tied to the coast north of Red Bluff and provides some sheltering for nearshore lagoons that widens to approximately 750m with distance to Gnaraloo Bay.	The WNW facing shoreline has four shallow embayments, each with a distinctive morphology. Beachrock, perched beaches and occasional sandy sections dominate the coast north of Red Bluff. Mainly cliffed coast exists south of Red Bluff, with some transgressive dunes ramping over them in places. Beachrock and adjacent barrier reeflines, formed coast with some beach formation between headlands north of Red Bluff.	Episodic transgressive barriers have formed in the northern reaches of the shallow embayments, with the exception of the small embayment immediately south of Red Bluff. These commonly have scarped foredunes and a 50 to 75% vegetation cover. Overall, the barriers have a 50 to 75% vegetation cover. They include mobile sand sheets and active dunes.
Point Quobba to Cape Cuvier	Between Point Quobba and Cape Cuvier the inner continental shelf is deep and steep close to shore, where the 10m isobath is within 1km of the rocky shore.	Undercut platforms along the W to WSW facing coast gradually merge with a steep, plunging cliff at Cape Cuvier. Perched beaches such as the beach at Quobba Station and Gnaraloo are found in localised embayments. The beaches are sheltered and have a rounded to reflective morphology.	Episodic transgressive dunes originating south of Point Quobba comprise a perched barrier. There are no foredunes and the trailing arms of the parabolic dunes are parallel to the shore although disturbed close to where the rock platforms are exposed. The dunes have a 50 to 75%, or higher, vegetation cover.
South Bejaling Hill to Point Quobba	Exposure of the coast to the open ocean and deeper water increases with distance northward from South Bejaling Hill to Point Quobba.; and the distance from the shore to the 10m isobath diminishes from approximately 12km to <1km. There also is an increase in intermittent reef and rock outcrop close to shore with distance north as the shoreface changes from a sandy to a rocky shore with intertidal rock platforms.	The shoreline has a broad, low-amplitude salient in the lee of the Fitzroy Reefs, together with a change in aspect from SW to WSW on either flank. The exposed sandy beach has a dissipative profile with continuous longshore bars present. In the north, the exposed beaches are perched on rock platforms. Occasional sections of coast may have a low undercut cliff face.	Beach ridges of the Bejaling progradational plain give way to a perched episodic transgressive dune with distance north. The foredunes are discontinuous, partly scarped and have <25% vegetation cover. The frontal dunes included mobile sand sheets and blowouts, particularly north of the southern end of Lake MacLeod. Overall vegetation cover is 25 to 50%.

SECONDARY COMPART.	INSHORE	SHORE	BACKSHORE
Grey Point to South Bejaling Hill	Offshore, the inner continental shelf waters are partly enclosed by Bernier and Dorre Islands. Closer to shore the shoreface is shallower, <10m, within approximately 10km of the coast, with sand banks and shoals present.	This is an area of transition from the sheltered tidal flats of the Wooramel Bank complex to sandy coast markedly affected by modern Gascoyne River and its geological antecedents, the Brown and Boodalia deltas. The coast is comprised of three segments: the seawardly convex features of the river deltas and the shallow zeta form of the sandy coast north of Miaboolya Beach to Bejaling Hill.	In the south, tidal flats with some channels controlled by protection from offshore and onshore reef systems may back onto low cliffs and sand ridges. The shores of the Brown and Boodelia delta complex include a series of discontinuous chenier ridges; approximately 1.5km wide, well vegetated tidal flats; and mangals. Tidal creeks are common, particularly on the northern flank of the delta. The Gascoyne Delta, which merges with the Bejaling Beach Ridge Complex, has active cheniers, spits, tidal creeks and foredunes. The beaches are sandy and have an exposed, reflective profile configuration.
Wooramel coast to Grey Point	A 40km wide channel 10-20m deep that opens to the NW fronts the coast between Wooramel coast and Grey Point. Further north and further offshore, Peron Peninsula, Dirk Hartog Island and Dorre Island provide shelter to Shark Bay from the west, although there is open water in the channel between the islands. Closer to shore there is a gradual rise to the sub-tidal platform of the Wooramel Bank and the pro-delta slopes of the Wooramel and Gascoyne rivers.	Tidal flat development is variable, with some sandy and or fine grained beach material forming the 10-15km wide, Wooramel Bank complex of tidal creeks and sub-tidal terraces along the coast. The shape of the rhythmic shoreline is controlled by tidal currents, local areas of rocky pavement, and the formation of spits and cheniers which impound wide, bare tidal flats to landward.	Barrier development is limited to the chenier and spit ridges, as well as intermittent reaches of foredune ridge along the shore. The spits, cheniers and foredune ridges support a 25 to 50% vegetation cover, and more in some places. Sheltered beaches along the cheniers and spits have a segmented or rounded profile and there is evidence of storm overwash.
Nilemah coast E to Wooramel coast	The compartment includes the Faure Sill and W facing coast south of the sill, adjoining the hypersaline basin of Hamlin Pool. The basin may be over 10m deep but is commonly between 5 and 10m. From the 5m isobath the basin floor grades gently to a broad sub-tidal terrace over 5km in width. The seaward edge of the sub-tidal terrace is irregular and rhythmic in form before merging with old, partly lithified pro-delta sediments of the Wooramel River.	Two shallow arcuate embayments form the W facing coast. They extend from Nilemah coast E to Yaringa Point and from there to Wooramel coast. Tidal flat development in the southern embayment is variable, with some sandy and/or fine grained beach material forming perched beaches. The beach form is controlled by protection from offshore and onshore reef systems. The northern embayment includes a smaller embayment, Hutchison Embayment, which has been cut off by a large spit and lithified deltaic features possibly associated with prior discharge from the Wooramel River.	Prograded barriers comprising foredune and beach ridge plains are a common feature of the southern embayment. The plains are up to 600m wide. The frontal dune ridge is higher with distance north from Nilemah coast E. There is 25 to 50% vegetation cover on the foredunes and 50 to 75% cover on the barriers. Cheniers, spits and tidal flats are more common features of the northern embayment where barrier development is limited. However, like the progradational plains of the southern coast these are perched on a rock pavement that extends seaward as a sub-tidal terrace. The beaches of the compartment are sheltered forms backed by low ridges and washover forms.

SECONDARY COMPART.	INSHORE	SHORE	BACKSHORE
Petit Point to Nilemah coast E	The compartment includes the Faure Sill and ENE facing coast south of the sill, adjoining the hypersaline basin of Hamlin Pool. The basin may be over 10m deep but is commonly between 5 and 10m. A broad, irregular sub-tidal terrace, with three large lithified spits or promontories varying in width up to 7km, projects into Hamlin Pool from shoreline salients.	Beachrock dominates the beaches with occasional sandy and shelly sand sections. Parts of the beachface may include a low undercut beachrock cliff face. The form of the sheltered, mixed sand and shelly beaches varies from segmented in areas where littoral drift is apparent to rounded or flat elsewhere depending on the mix of sedimentary material. The beaches are commonly perched on beachrock and large spits indicate a northerly littoral drift.	Extensive progradational plains comprised of beach ridges, cheniers and storm ridges back broad beaches and bare tidal flats along the coast between Petit Point and Nilemah coast E. The plains are irregular in form and range in width to over 600m. They are perched on a sub-tidal pavement. In some cases there is a high foredune ridge similar in form to a storm ridge. The frontal dunes and the plains have a 25 to 50% vegetation cover.
Monkey Mia to Petit Point	The compartment encompasses L'Haridon Bight and the Faure Sill west of Faure Island and Petit Point. Centrally, the L'Haridon Bight basin is over 10m deep but a broad sub-tidal terrace, varying in width up to 5km, shelves gently from the 2.5m to 10m isobath. The seaward edge of the sub-tidal terraces on the east and west facing coasts is irregular and rhythmic in form.	Beachrock dominates E and NW facing beaches with extensive shelly sections such as the beach ridge sequence at Shelly Beach. Away from the head of L'Haridon Bight there are well developed spits indicating a northerly littoral drift on the E and W facing shores. Parts of the beachface may include a low undercut beachrock cliff face. The form of the sheltered, mixed sand and shelly beaches varies from segmented in areas where littoral drift is apparent to rounded or flat elsewhere depending on the mix of sedimentary material.	Barrier development is limited to small foredune plains such as that at Monkey Mia and narrow ridges of transgressive dunes abutting or overlying older Pleistocene dunes. The vegetation cover varies but is commonly between 50 and 75% on the foredunes and frontal dunes. The spits are unvegetated and show evidence of storm washover. They impound shallow tidal flats.
Cape Peron North to Monkey Mia	This section of coast faces the waters of Hopeless Reach, a basin open to the NNW and on the northern side of the Faure Sill, an extensive complex of sand banks and rock separating Hopeless Reach from the hypersaline waters of Hamelin Pool and L'Haridon Bight. In an east-west cross section, the basin is asymmetric with the deepest part, over 10m deep, in the west. Along the eastern shore the bathymetry shallows to <5m approximately 15km offshore and rises to the broad intertidal shoals, tidal creeks and spits of the Wooramel Bank.	Three zeta-form bays comprise the NE facing shoreline between Point Peron and Eastern Bluff at Monkey Mia. The headlands are associated with wide sub-tidal terraces and, at Herald Bluff, and extensive spit formation at Guichenault Point. Beachrock dominates the beaches with occasional sandy and shelly sand sections. Parts of the beachface may include a low undercut beachrock cliff face. The form of the sheltered, mixed sand and shelly beaches varies from segmented in areas where littoral drift is apparent, to rounded or flat elsewhere depending on the mix of sedimentary material.	Barrier development is limited to small foredune plains such as that at Monkey Mia and narrow ridges of transgressive dunes abutting or overlying older Pleistocene dunes. The vegetation cover varies but is commonly between 50 and 75% on the foredunes and frontal dunes.

SECONDARY COMPART.	INSHORE	SHORE	BACKSHORE
Goulet Bluff to Cape Peron North	The west coast of the Peron Peninsula, between Goulet Bluff and Cape Peron North is separated from the eastern shore of the Freycinet Channel and Denham Sound by a channel that is over 10m deep and widens from approximately 15km in the south to 50km at its mouth. Closer to shore the water is less than 5m deep in a widening lens up to 15km from the shore.	Neglecting the Dampier Limestone outcrops at Point Peron, five large rocky headlands and a number of minor ones control the shape of the coast: Goulet Bluff, Eagle Bluff, Lagoon Point, Middle Bluff and Cape Lesuer. Much of the coast has low limestone cliffs. Sandy sub-tidal terraces and shoals, the widest over 4.5km wide, are tied to each of the headlands. The sheltered beaches along the coast are formed of a mixture of sandy and shelly sediments and many are perched on a beachrock pavement. They have segmented to rounded profiles depending on the degree of protection provided by the sub-tidal terraces.	Barrier development is limited although narrow beachridge and foredune plains are inset into the heads of some small embayments. The small plains are well vegetated with 50 to 75% cover.
Giraud Point to Goulet Bluff	The semi-enclosed hypersaline basin of Henri Freycinet Harbour comprises the offshore waters of this compartment. The basin is open to the north west where it joins Denham Sound through Freycinet Reach. It is asymmetric with the deepest part (>10m) in the eastern part of the basin, with waters less than 5m deep approximately 3km off its eastern shore.	The south western part of the basin has an irregular shoreline with small embayments and headlands flanked by wide sub-tidal terraces. To the east of Salutation Island the west facing coast is arcuate in plan form, with two shallow embayments separated by a rocky headland. Spits are tied to all irregularities along the coast and are superimposed on a sub-tidal platform varying in width from 1 to 2.5 km. The beaches have a sheltered, segmented or rounded, form and are commonly perched on beachrock. The sub-tidal terrace narrows and closes with the shore on the SW facing, northern end of the arcuate embayment.	Barrier development is limited. A well vegetated (50 to 75% cover) foredune ridge is present in many places and in some places a narrow foredune plain is present.
Cape Bellefin to Giraud Point	A series of N-S trending peninsulas separated by three, narrow shallow-water bodies are the main features of this compartment; Useless Inlet, Brown Inlet and Depuch Loop. Remnant and active sub-tidal terraces adjoin the shore on each the peninsulas and shoals occur in central parts of the water bodies, particularly in trhe northern part of Useless Inlet.	The sub-tidal terraces vary in width but are commonly <3km wide. The shorelines are geologically controlled with a mixture of rocky and sandy coast, and are irregular in planform with numerous bays on predominantly E and W facing shores. The sandy beaches are sheltered, commonly have a flat or segmented profile and are commonly perched on beachrock. Spits provide evidence of littoral drift along parts of the shores.	Barrier development is limited. A well vegetated (50 to 75% cover) foredune ridge is present in many places.

SECONDARY COMPART.	INSHORE	SHORE	BACKSHORE
Cape Inscription to Cape Bellefin	This compartment includes the eastern shore of Dirk Hartog Island and the South Passage between Surf Point and Steep Point. Although not completely surveyed the bathymetry includes areas of shallow, sub-tidal terrace extending to a depth of approximately 5m 2-3 km offshore. The seabed is commonly sandy and supports seagrass meadows in places.	The mainly ENE facing, sheltered shore is structurally compartmentalised into discrete sediment cells. Sandy beach morphology varies from extremely sheltered forms to reflective beaches with exposure.	Cuspate forelands, spits and narrow foredune plains are present in the northern section of the compartment and the northernmost tip supports a perched, episodic transgressive barrier. The foredunes and barriers have 50 to 75% vegetation cover. An unusual feature on the southern part of the island is a mobile parabolic dune that has crossed the island from the west to east coast.
Steep Point to Cape Inscription	The seabed rises steeply along the western shore of Dirk Hartog Island and generally is over 20m deep seaward of 1.5km offshore. Deep intermittent reef may exist close to shore as a result of cliff erosion.	The coastal aspect is varied, ranging from SW along the northern third of the island to NW close to Cape Inscription. Most of the coast is formed of continuous, high limestone cliffs and is an extension of the Zuytdorp Cliffs.	There are no barriers in this compartment although Holocene dunes are present as parabolic dunes on the cliff top along the southern third and in northern parts of the island.
Nunginjay Spring coast N to Steep Point	North of the Nunginjay Spring coast N the 20m isobath approximately parallels the coast and is over 70km offshore until it closes with the coast near Dulverton Bay (False Entrance) and is within 2km of the shore at Steep Point.	The Zuytdorp Cliffs are the major feature between Nunginjay Spring coast N and Steep Point. Steeply sloping bluffs merge into continuous limestone cliff with distance north. The steep cliff face is undercut in eroding limestone. In the northern part of the compartment the high cliffs face approximately WSW and are continuous. They have intertidal platforms before plunging to sub-tidal levels.	Barrier development is limited and barriers are not present on much of the coast. Episodic transgressive barriers with mobile sand sheets and mainland barriers are apparent in parts of the compartment, as are cliff top dunes.
Murchison River to Nunginjay Spring coast N	The compartment between the mouth of the Murchison River and Nunginjay Spring coast N identifies coast most affected by river discharge. The inshore bathymetry includes an embayment to the NW of Oyster Reef which is apparent in the 10 and 15m isobaths. These are within 500m of the shore and include seabed rising to sandstone platform along the coast.	The orientation of the coast changes to a WNW aspect north of the mouth of the Murchison River. The shore has several components: the river mouth with its rock platform and bars; a 5km reach of sandy beach perched on rock platform abutting a rocky coast; and 5.5km of perched beach abutting mobile parabolic dunes. The beaches are exposed and have a reflective morphology.	Two barrier components form part of the compartment north of the river mouth. A mainland beach extends approximately 5km immediately north of the river mouth, with cliff top dunes overlying a calcarenite surface. The foredune on this section of coast has between 25 and 75% cover. Further north are nested parabolic dunes characteristic of an episodic transgressive barrier. This abuts and overlies older dune topography and calcarenite cliffs. The vegetation cover is variable, but generally >50%, and a mobile sand sheet is immediately south of Nunginjay Spring. A high foredune ridge along this section of coast has 25 to 75% cover, small blowouts and is scarped along its seaward margin.

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Appendix F Secondary Compartment Susceptibility, Instability and Vulnerability Rankings and Implications

SUSCEPTIBILITY AND INSTABILITY RANKINGS SHOULD NOT BE USED INDEPENDENTLY. BOTH ARE BASED ON SEVERAL CRITERIA AND ARE GUIDES TO THE VULNERABILITY ASSESSMENT

Secondary Comp.	From Long.	From Lat.	Susceptibility		Instability		Vulnerability		
			Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Giralia to Locker Point	114.293	-22.4368	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
Learmonth to Giralia	114.0928	-22.2038	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
North West Cape to Learmonth	114.1652	-21.7854	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Winderabandi Point to North West Cape	113.7059	-22.4941	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.

Secondary Comp.	From Long.	From Lat.	Susceptibility		Instability		Vulnerability		
			Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Point Cloates to Winderabandi Point	113.673	-22.7197	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
Point Maud to Point Cloates	113.7593	-23.1217	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Alison Point to Point Maud	113.7661	-23.4938	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Gnaraloo Bay to Alison Point	113.5522	-23.766	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Cape Cuvier to Gnaraloo Bay	113.3914	-24.2231	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.

Secondary Comp.	From Long.	From Lat.	Susceptibility		Instability		Vulnerability		
			Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Point Quobba to Cape Cuvier	113.4079	-24.4909	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
South Bejaling Hill to Point Quobba	113.569	-24.6777	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
Grey Point to South Bejaling Hill	113.7517	-25.131	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
Wooramel coast to Grey Point	114.1741	-25.8074	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
Nilemah coast E to Wooramel coast	114.0824	-26.4463	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.

Secondary Comp.	From Long.	From Lat.	Susceptibility		Instability		Vulnerability		
			Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Petit Point to Nilemah coast E	113.8745	-25.9441	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Monkey Mia to Petit Point	113.7219	-25.7933	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Cape Peron North to Monkey Mia	113.5106	-25.5039	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Goulet Bluff to Cape Peron North	113.6876	-26.2162	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Giraud Point to Goulet Bluff	113.6303	-26.4629	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.

Secondary Comp.	From Long.	From Lat.	Susceptibility		Instability		Vulnerability		
			Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Cape Bellefin to Giraud Point	113.2995	-26.0151	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Cape Inscription to Cape Bellefin	112.9712	-25.4795	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
Steep Point to Cape Inscription	113.1591	-26.1431	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Nunginjay Spring North to Steep Point	114.1248	-27.5744	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
Murchison River to Nunginjay Spring N	114.1599	-27.7061	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.

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Appendix G Areas of Planning Interest Landforms and Sediment Cells

Each sub-appendix contains a: vulnerability map; landform map; cell description; and cell susceptibility, instability and vulnerability rankings and implications.

Appendix G1: Nanga
Appendix G2: Denham area – Denham & Little Lagoon
Appendix G3: Monkey Mia
Appendix G4: Carnarvon area – Carnarvon& Miaboolya Beach
Appendix G5: Quobba-Blowholes area – Blowholes & Quobba Station
Appendix G6: Gnaraloo area - Red Bluff, Three Mile Camp, Gnaraloo Station & Gnaraloo Bay
Appendix G7: Coral Bay
Appendix G8: Vlamingh Head
Appendix G9: Exmouth

Appendix G1 Nanga

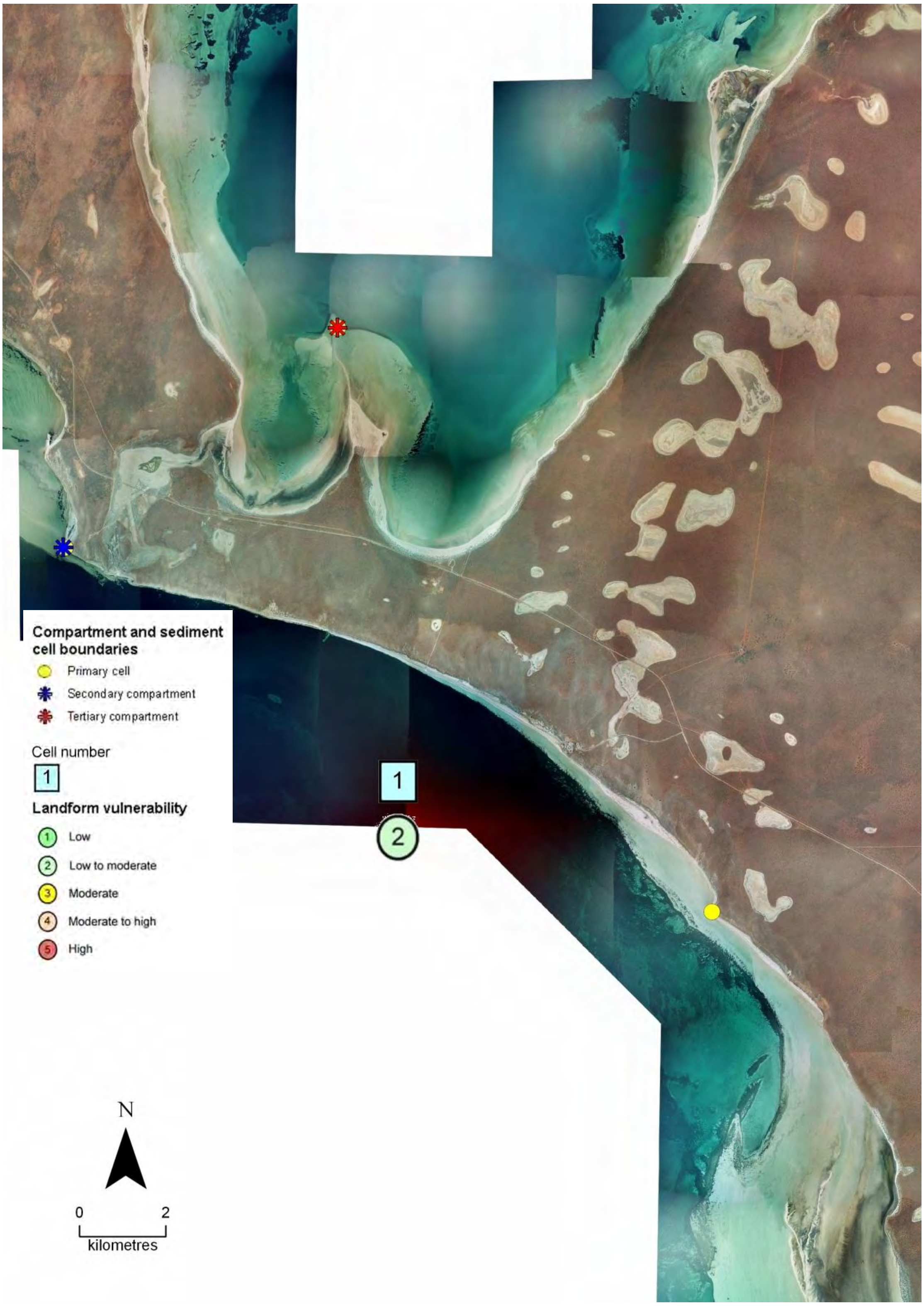

Figure G-1: Nanga Vulnerability

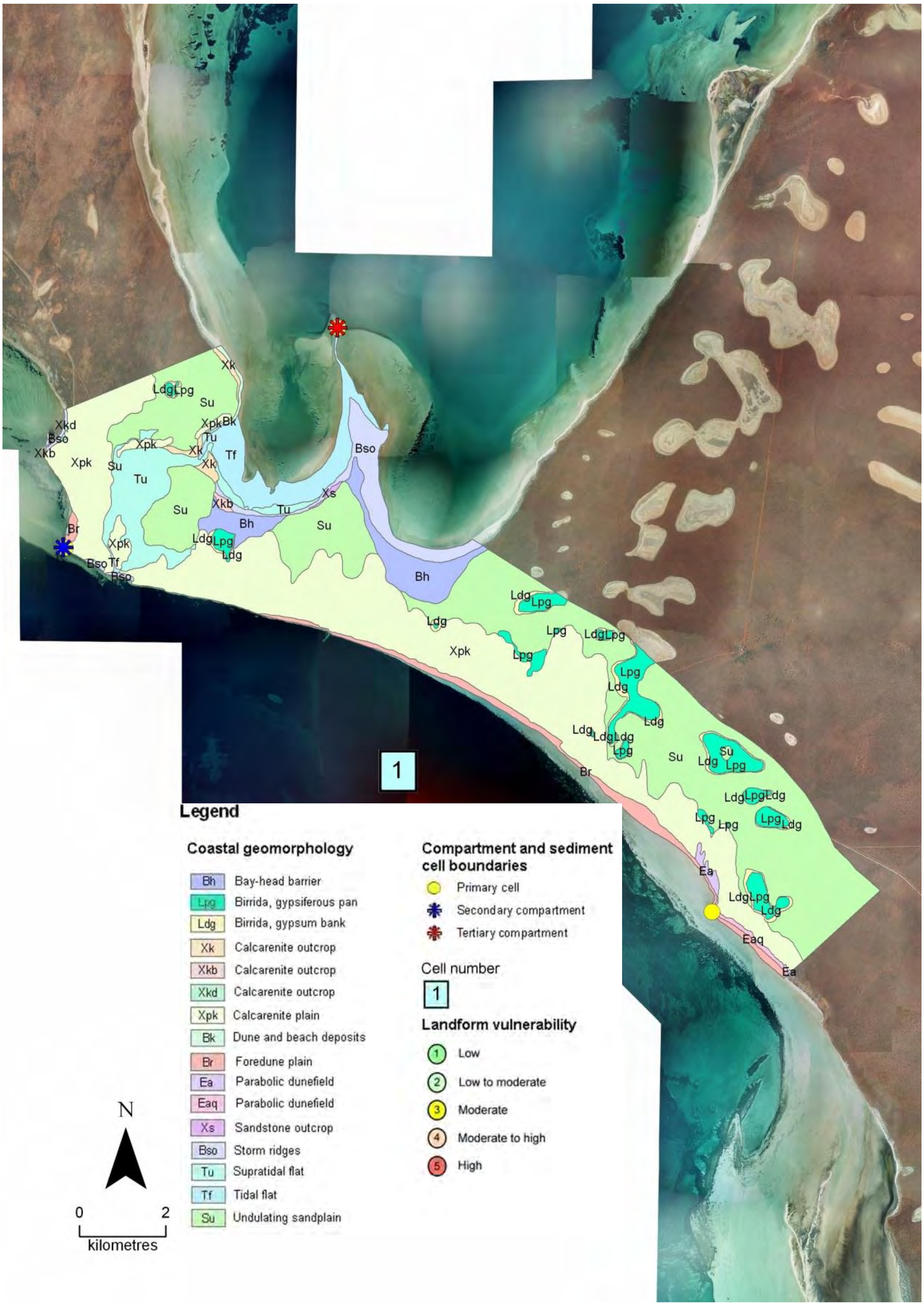

Figure G-2: Nanga Landforms

Table G-1: Landforms of the Nanga Area and their Relative Instability (After: Gozzard 2012). See Table2- for Explanation of Colour Codes

Landform	Description	Relative Instability
Bay-head barrier (Bh)	Prograded barrier of multiple storm beach shelly shingle ridges infilling former marine embayments.	Low (Stable)
Birrida, gypsiferous pan (Lpg)	Flat, raised pan, often elliptical in shape; soils are red or reddish yellow sandy clays overlying gypsiferous sands.	High (Unstable)
Birrida, gypsum bank (Ldg)	Undulating mounds up to 3 m above the surrounding sandplain, occurring as banks or dune-like accumulations; soils are generally thin layers of reddish brown sand over gypsiferous deposits.	Moderate
Calcarenite outcrop (Xk)	Isolated small outcrops of shelly calcarenite to calcirudite of undivided Bibra and Dampier Limestones of Middle Pleistocene age; extensively calcreted upper surfaces.	Moderate
Calcarenite outcrop (Xkb)	Isolated small outcrops of shelly calcarenite to calcirudite of Bibra Limestone of Middle Pleistocene age; extensively calcreted upper surfaces.	Moderate
Calcarenite outcrop (Xkd)	Isolated small outcrops of shelly calcarenite to calcirudite of Dampier Limestone of Middle Pleistocene age; extensively calcreted upper surfaces.	Moderate
Calcarenite plain (Xpk)	Undulating coastal plains with parabolic rocky ridges and outcrops of limestone; developed on Tamala Limestone; densely mantled with limestone pebbles or cobbles; soils are reddish brown loamy sands with limestone inclusions.	Low (Stable)
Dune and beach deposits (Bk)	Relatively narrow shore-parallel dune-beach fringe of pink to light brown loose sands.	High (Unstable)
Foredune plain (Br)	Narrow, low undulating plains composed of several parallel individual low foredune ridges rarely exceeding 5 m in height; soils are pink or light brown loose calcareous sands.	Moderate
Parabolic dunefield (Ea)	Small-scale low, stabilised parabolic dunes as veneer over Tamala Limestone; soils are non-coherent light brown or pink calcareous sands.	Moderate
Parabolic dunefield (Eaq)	Small-scale low, stabilised parabolic dunes; soils are light red sands.	Moderate
Sandstone outcrop (Xs)	Isolated small outcrop of red quartzose sandstone of Peron Sandstone of Middle Pleistocene age; calcrete zone on the upper surface.	Moderate
Storm ridges (Bso)	Loose to indurated and calcreted supra-tidal ridges of coquina shells deposits up to 8 m above tidal mudflats.	High (Unstable)
Supratidal flat (Tu)	Isolated, unvegetated, low gradient mudflat; only inundated during extreme high tides and storm surge events; soils are calcareous silts and sands.	High (Unstable)
Tidal flat (Tf)	Infrequently inundated halophyte mudflats; soils are silts and clays.	High (Unstable)
Undulating sandplain (Su)	Flat to gently undulating sand sheets, generally without dune development; no drainage features; soils are red to brown sands.	Low (Stable)

Table G-2: Nanga Sediment Cell Description

Cell	S	N	INSHORE	SHORE	BACKSHORE
1	Nanga Bay	Goulet Bluff	The broad sub-tidal terrace present in the southern part of Henri Freycinet Harbour narrows and closes with the shore approximately 7km ESE of Goulet Bluff. The 5m isobath changes from approximately 2km to 0.5km offshore along the Taillefer Isthmus, between the southern headland at Nanga Bay and Goulet Bluff.	Aspect changes around the SW facing embayment increasing exposure to southerly winds with distance west. The sheltered beach narrows with distance north and the shore grades to limestone cliff at Goulet Bluff. Beach profiles are segmented or rounded. Some sections of the coast have beach ridges that have been overwashed.	Barrier development is limited to a narrow foredune ridge or foredune plain, as occurs at Nanga. In much of the cell the dunes abut and overtop a limestone cliff. Perched dunes are present along much of the southern section of the embayment. The foredunes have a 25 to 50% vegetation cover. This vegetation cover increases with distance landward where small foredune plains are present.

Table G-3: Nanga Sediment Cell Susceptibility, Instability & Vulnerability Rankings

Sediment Cell	Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
1	Nanga Bay to Goulet Bluff	1	2	3	5	11	M	4	1	2	2	9	L	2	L-M

Table G-4: Nanga Sediment Cell Susceptibility, Instability and Vulnerability Rankings and Implications

Susceptibility and Instability Rankings should not be used independently.

No.	Cell	From Long.	From Lat.	To Long	To Lat.	Susceptibility		Instability		Vulnerability		
						Rank	Implications	Rank	Implications	Rank	Risk	Rationale
1	Nanga Bay to Goulet Bluff	113.8395	-26.2894	113.6879	-26.2162	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.

Appendix G2 Denham Area

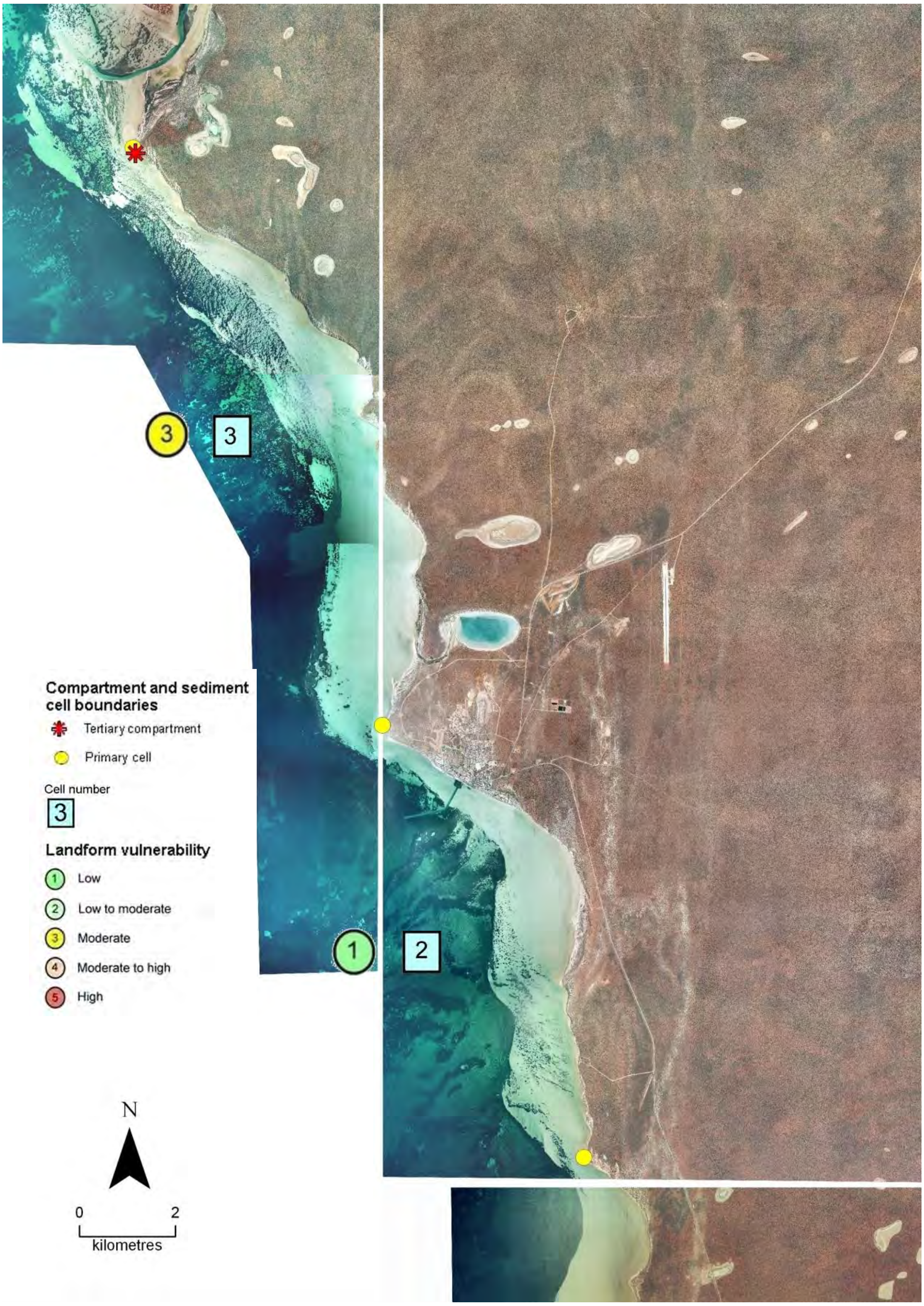

Figure G-3: Denham Area Vulnerability

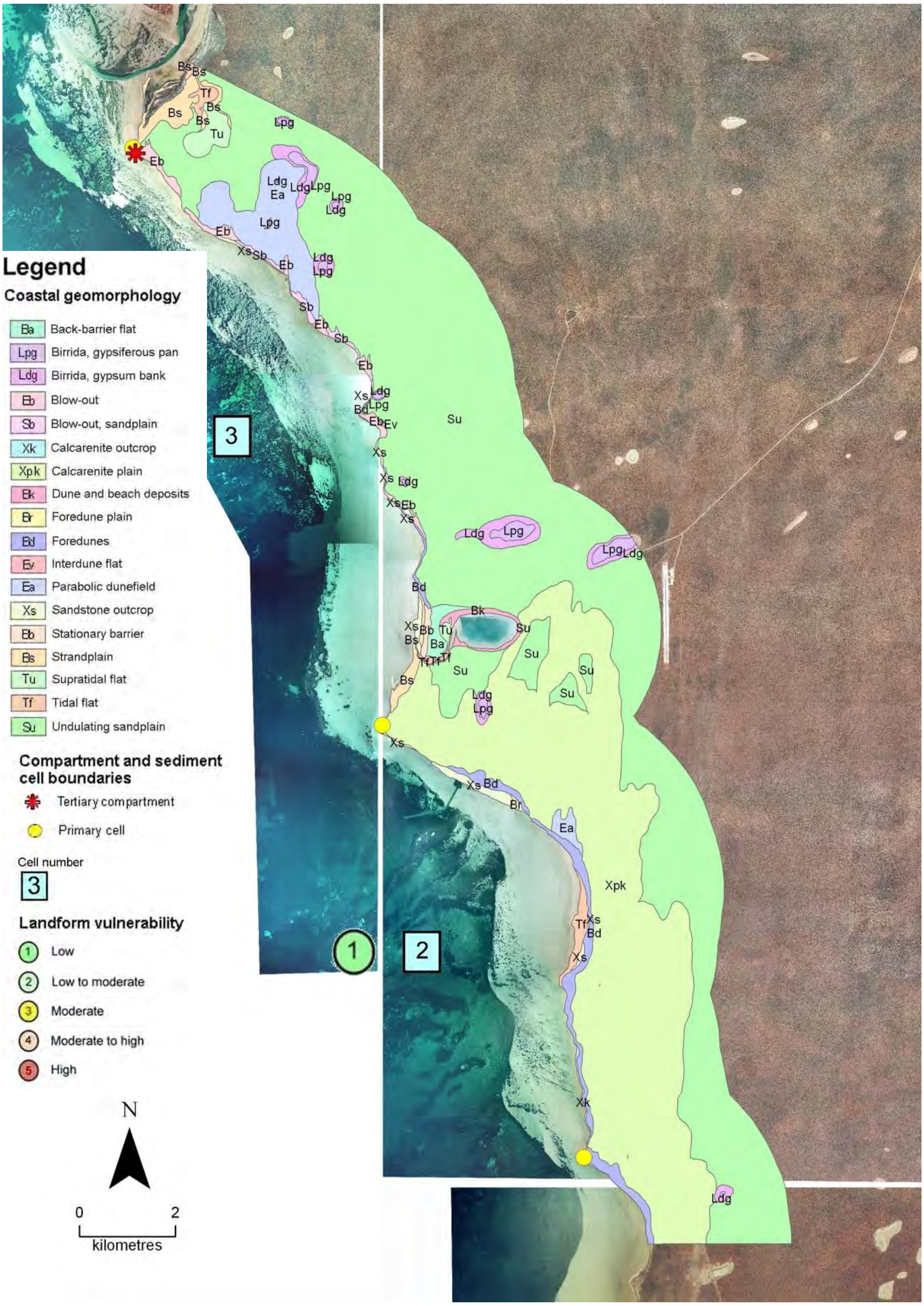

Figure G-4: Denham Area Landforms

Table G-5: Landforms of the Denham Area and their Relative Instability (After: Gozzard 2012). See Table2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Back-barrier flat (Ba)	Gently sloping flat ground on the Little Lagoon side of the stationary barrier composed predominantly of sand washed over or through the barrier during tidal surges.	Moderate
Birrida, gypsiferous pan (Lpg)	Flat, raised pan, often elliptical in shape; soils are red or reddish yellow sandy clays overlying gypsiferous sands.	High (Unstable)
Birrida, gypsum bank (Ldg)	Undulating mounds up to 3 m above the surrounding sandplain, occurring as banks or dune-like accumulations; soils are generally thin layers of reddish brown sand over gypsiferous deposits.	Moderate
Blow-out (Eb)	Isolated active parabolic dunes with arcuate crests and steep north-facing slopes; soils are loose light brown or pink calcareous sands.	High (Unstable)
Blow-out, sandplain (Sb)	Low coastal dunes and banks; soils are light red sands.	High (Unstable)
Calcarenite outcrop (Xk)	Isolated small outcrops of shelly calcarenite to calcirudite of undivided Bibra and Dampier Limestones of Middle Pleistocene age as shoreline reefs 7 km south of Denham; extensively calcreted upper surfaces.	Moderate
Calcarenite plain (Xpk)	Undulating coastal plains with parabolic rocky ridges and outcrops of limestone; developed on Tamala Limestone; densely mantled with limestone pebbles or cobbles; soils are reddish brown loamy sands with limestone inclusions.	Low (Stable)
Dune and beach deposits (Bk)	Relatively narrow shore-parallel dune-beach fringe comprising one or two major dune ridges of pink to light brown loose sands.	High (Unstable)
Foredune plain (Br)	Narrow, low undulating plain at Denham composed of several parallel individual low foredune ridges rarely exceeding 5 m in height; soils are pink or light brown loose calcareous sands.	Moderate
Foredunes (Bd)	Relatively narrow shore-parallel fringe comprising one or two low ridges of pink to light brown loose calcareous sand.	High (Unstable)
Interdune flat (Ev)	Interdunal corridors in parabolic dunefield with undulating calcareous sandy floors.	Low (Stable)
Parabolic dunefield (Ea)	Small- to large-scale low, stabilised long-walled parabolic dunes; soils are non-coherent light brown or pink calcareous sands.	Moderate
Sandstone outcrop (Xs)	Isolated small outcrops of red quartzose sandstone of Peron Sandstone of Middle Pleistocene age 8 km north and 4 km south of Denham; calcrete zone on the upper surface.	Moderate
Stationary barrier (Bb)	Relatively narrow, shore-parallel dune-beach fringe west of Little Lagoon comprising a single well vegetated major dune ridge; some eolian reworking.	Moderate
Strandplain (Bs)	Narrow plain west of Denham; up to 300 m wide, thin to thick bedded sand with minor muddy sand comprising beach, beach ridge and, tidal flat depositional areas.	High (Unstable)
Supratidal flat (Tu)	Isolated, unvegetated, low gradient mudflat; only inundated during extreme high tides and storm surge events; soils are calcareous silts and sands.	High (Unstable)
Tidal flat (Tf)	Infrequently inundated halophyte mudflats; soils are silts and clays.	High (Unstable)
Undulating sandplain (Su)	Undulating sandy plain with linear to reticulate, northeast-trending dunes; soils are red to brown sands.	Low (Stable)

Table G-6: Denham Area Sediment Cell Description

Cell	S	N	INSHORE	SHORE	BACKSHORE
3	Lagoon Point	Middle Bluff	The sub-tidal terrace along the shore is approximately 1.4-2km wide. The outer third is partly vegetated and has an arcuate seaward margin parallel to the coastline. Sand ridges, bars and small spits are apparent on the sandy surface of the sud-tidal terrace close to shore.	The shoreline is a shallowly-indented, arcuate embayment facing WSW. Shoreline irregularities within the broader structure are related to smaller rocky headlands and bays. The sheltered beaches are commonly perched and extend discontinuously along the coast, alternating with reaches of cliff. The beach profiles are segmented to rounded in form.	With the exception of the 3km long and approximately 250m wide chenier and spit plain at the mouth of Little Lagoon, barrier development is limited to mainland beaches on which barrier sands abut and residually overlie rocky coast. There are localised patches of nested blowouts and parabolic dunes on the southern flanks of the small headlands in the cell. Foredunes are discontinuous and alternate with reaches of cliffed coast. The vegetation cover on the dunes is between 25 and 50%.
2	Denham South	Lagoon Point	A broad sub-tidal terrace flanks the shore between Denham South and Lagoon Point. It is widest, up to 1.7km, in the south and narrowest, approximately 500m wide, between Denham townsite and Lagoon Point.	There are three components to the shoreline in this cell. From south to north it includes a 3.8km reach of nearly-straight, WSW-facing rocky coast; 2.5km of tidal flat in a shallow embayment north of the Oceanarium; and approximately 4.5km of nearly straight coast along the Denham shore, part of which is sandy and part rocky. The sheltered beaches along the coast are formed of a mixture of sandy and shelly sediments and many are perched on a beachrock pavement. They have segmented to rounded profiles depending on the degree of protection provided by the sub-tidal terraces. Denham was originally constructed on a storm bar and tidal flat not unlike that near the Oceanarium.	Barrier development is limited although narrow beachridge and foredune plains are inset into the heads of some small embayments cut into the Tamala Limestone escarpment. The small plains are well vegetated with 50 to 75% cover. A narrow storm ridge with washover features impounds a narrow tidal flat immediately north of the Oceanarium.

Table G-7: Denham Area Sediment Cell Susceptibility, Instability & Vulnerability Rankings

Sediment Cell	Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
3	Lagoon Point to Middle Bluff	1	1	3	5	10	M	3	2	3	3	11	M	3	M
2	Denham South to Lagoon Point	1	1	2	5	9	L	3	2	2	2	9	L	1	L

Table G-8: Denham Area Sediment Cell Susceptibility, Instability and Vulnerability Rankings and Implications

Susceptibility and Instability Rankings should not be used independently.

No.	Cell	From Long.	From Lat.	To Long	To Lat.	Susceptibility		Instability		Vulnerability		
						Rank	Implications	Rank	Implications	Rank	Risk	Rationale
3	Lagoon Point to Middle Bluff	113.5171	-25.918	113.4628	-25.8099	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
2	Denham South to Lagoon Point	113.5609	-25.9988	113.5171	-25.918	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.

Appendix G3 Monkey Mia

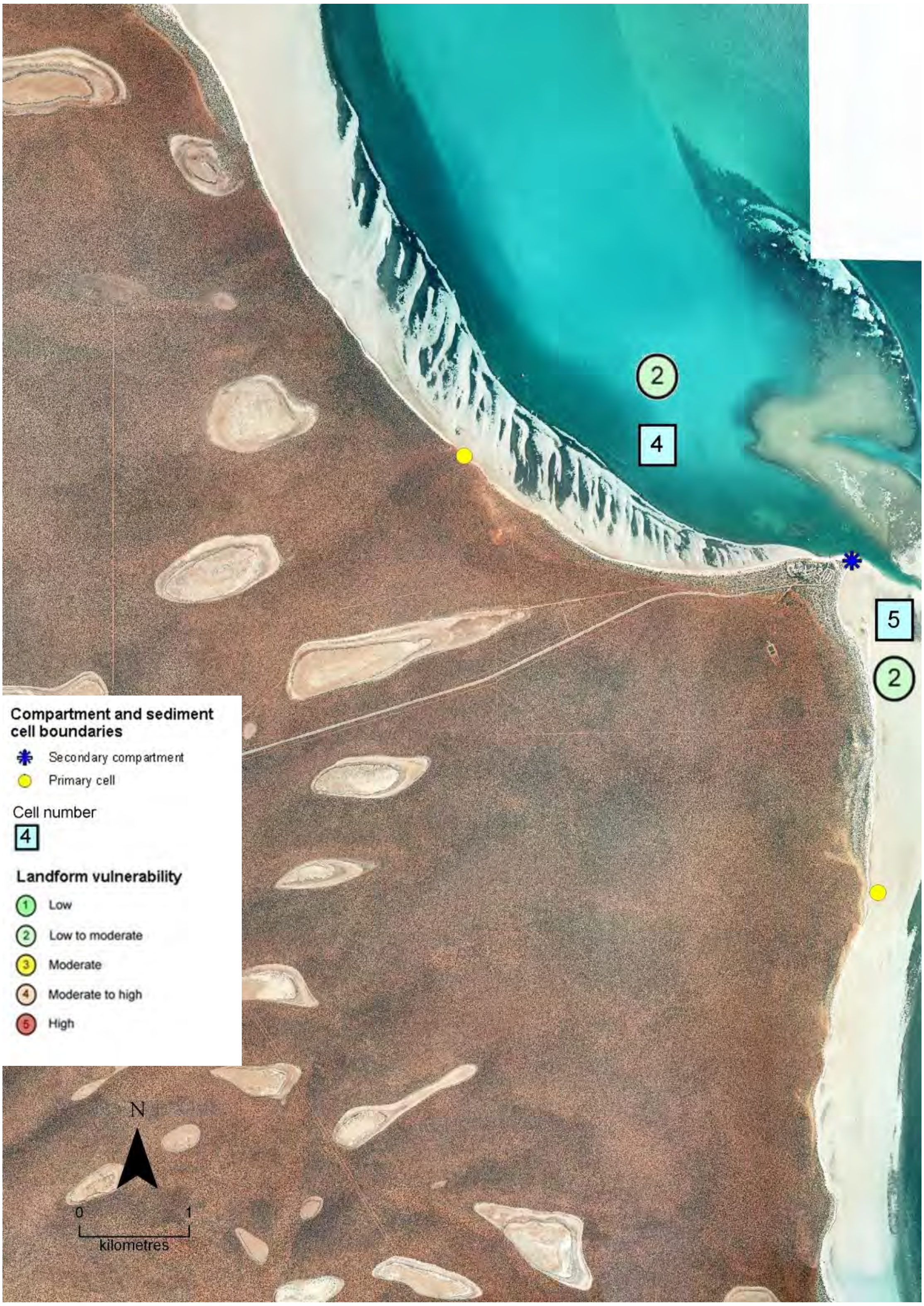

Figure G-5: Monkey Mia Vulnerability

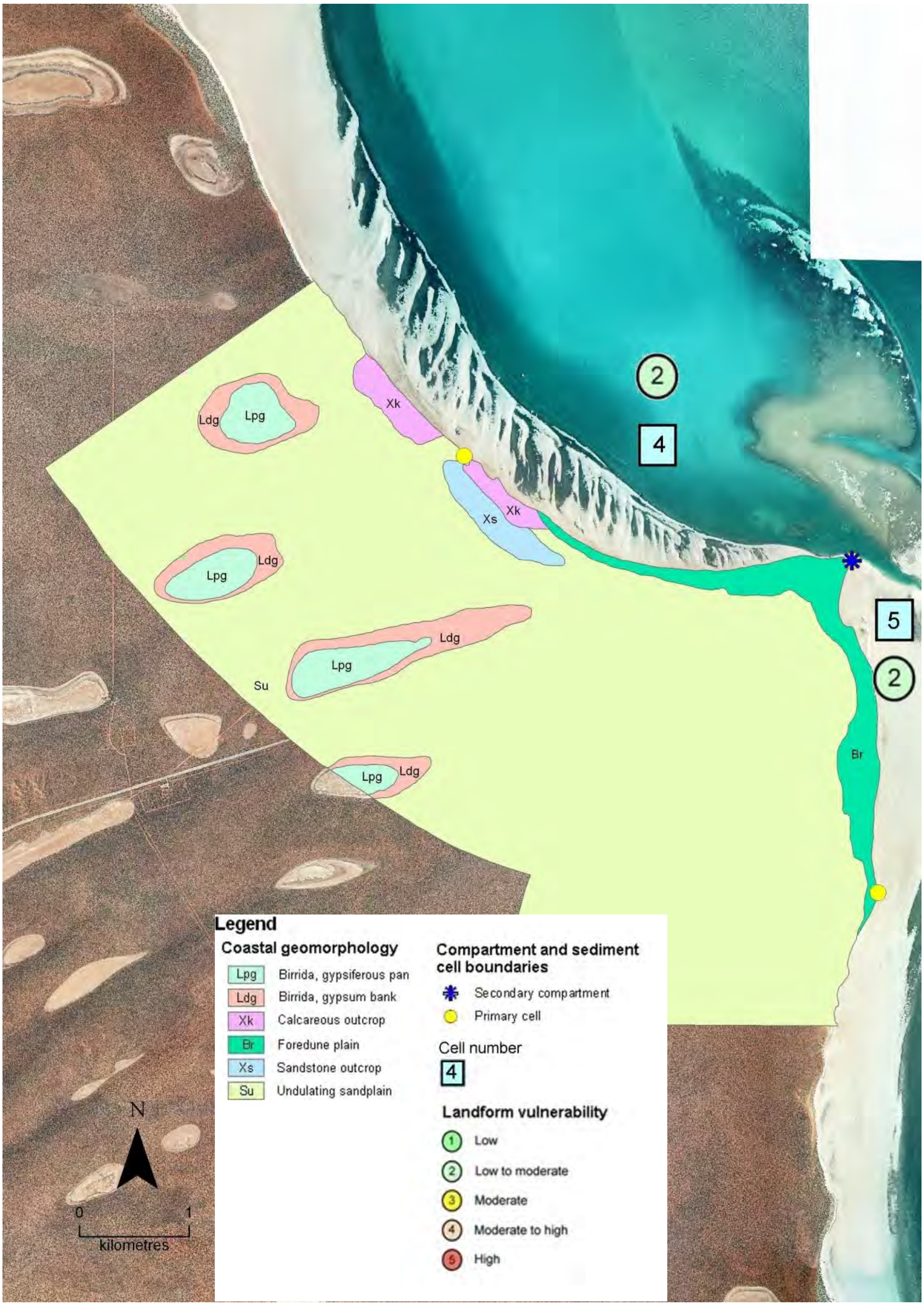

Figure G-6: Monkey Mia Landforms

Table G-9: Landforms of the Monkey Mia Area and their Relative Instability (After: Gozzard 2012). See Table2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Birrida, gypsiferous pan (Lpg)	Flat, raised pan, often elliptical in shape; soils are red or reddish yellow sandy clays overlying gypsiferous sands.	High (Unstable)
Birrida, gypsum bank (Ldg)	Undulating mounds up to 3 m above the surrounding sandplain, occurring as banks or dune-like accumulations; soils are generally thin layers of reddish brown sand over gypsiferous deposits.	Moderate
Calcarenite outcrop (Xk)	Isolated small outcrops of shelly calcarenite to calcirudite of Dampier Limestone of Middle Pleistocene age as shoreline reefs and low ridges along Red Cliff Bay; extensively calcreted upper surfaces.	Moderate
Foredune plain (Br)	Narrow, low undulating plain at Monkey Mia composed of several parallel individual low foredune ridges rarely exceeding 5 m in height; soils are pink or light brown loose calcareous sands.	Moderate
Sandstone outcrop (Xs)	Isolated narrow outcrop of red quartzose sandstone of Peron Sandstone of Middle Pleistocene age as a low ridge along Red Cliff Bay; calcrete zone on the upper surface.	Low (Stable)
Undulating sandplain (Su)	Undulating sandy plain with linear to reticulate, northeast-trending dunes; soils are red to brown sands.	Low (Stable)

Table G-10: Monkey Mia Secondary Sediment Cell Description

Cell	S	N	INSHORE	SHORE	BACKSHORE
5	Monkey Mia	Eastern Bluff	In the centre of the cell a 600m wide sub-tidal terrace overlies a 750m wide platform. Although with a slight increase in width from south to north the two features are continuous along the coast. Shore parallel ridges, bars and small spits oriented in a northerly direction are apparent close to the beach.	The E facing shoreline is slightly convex to seaward but terminates with a 450m long spit and a small zeta-form embayment on the easter (S) flank of a cuspate foreland at Monkey Mia. Small spits, commonly less than 150m long, are present along the waterline. The sheltered beaches are narrow and have a rounded or reflective profile.	Holocene sediments comprising the modern beach and dune abut, overlie and have infilled embayments in older sediments. The distribution of the dunes is discontinuous along the coast and a moderately high (5 to 10m) frontal dune ridge of nested blowouts has formed. Foredunes are lacking and the vegetation cover of the localised mainland barriers is between 50 and 75%. Some parts of the coast have narrow, low-lying chenier plains and tidal flats close to the shore.
4	Red Cliff Bay	Monkey Mia	An extensive sub-tidal terrace partly overlies a rock platform between Cape Rose and Monkey Mia. It closes with the coast at Monkey Mia, is approximately 700 metres wide at Red Cliff Bay and is over 1.5km wide at Cape Rose. Large N-S trending ridges cross the sub-tidal terrace and swales between them support vegetation. The ridges coalesce to form a continuous sand sheet close to shore.	The shoreline of the NNE facing bay has a shallowly-indented, arcuate plan form, and has a subdued rhythmic shape. The curve of the arc is broken by outcrops of Dampier Limestone and other Pleistocene sediments that give colour to Red Cliff Bay. The perched beach extends continuously along the shore. It is sheltered by the platform and sub-tidal terrace, and has a segmented to reflective profile shape.	A low beachridge plain comprises the cuspate foreland at Monkey Mia. It diminishes in width from approximately 300m at Monkey Mia, at the point of the Pleistocene sediment outcrop, to merge with the beach approximately 1km from Red Cliff Bay, where foredunes are absent and the low cliffs (5 to 10m in height) are present. Vegetation cover on the foreland and its westerly extension is between 50 and 75%.

Table G-11: Monkey Mia Sediment Cell Susceptibility, Instability & Vulnerability Rankings

Sediment Cell	Secondary Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
5	Monkey Mia to Eastern Bluff	1	1	3	5	10	**M**	3	2	2	2	9	**L**	2	**L-M**
4	Red Cliff Bay to Monkey Mia	1	1	3	5	10	**M**	3	1	2	2	8	**L**	2	**L-M**

Table G-12: Monkey Mia Sediment Cell Susceptibility, Instability and Vulnerability Rankings and Implications

Susceptibility and Instability Rankings should not be used independently.

No.	Cell	From Long.	From Lat.	To Long	To Lat.	Susceptibility		Instability		Vulnerability		
						Rank	Implications	Rank	Implications	Rank	Risk	Rationale
5	Monkey Mia to Eastern Bluff	113.7219	-25.7933	113.7249	-25.8205	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
4	Red Cliff Bay to Monkey Mia	113.6865	-25.7853	113.7219	-25.7933	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.

Appendix G4 Carnarvon Area

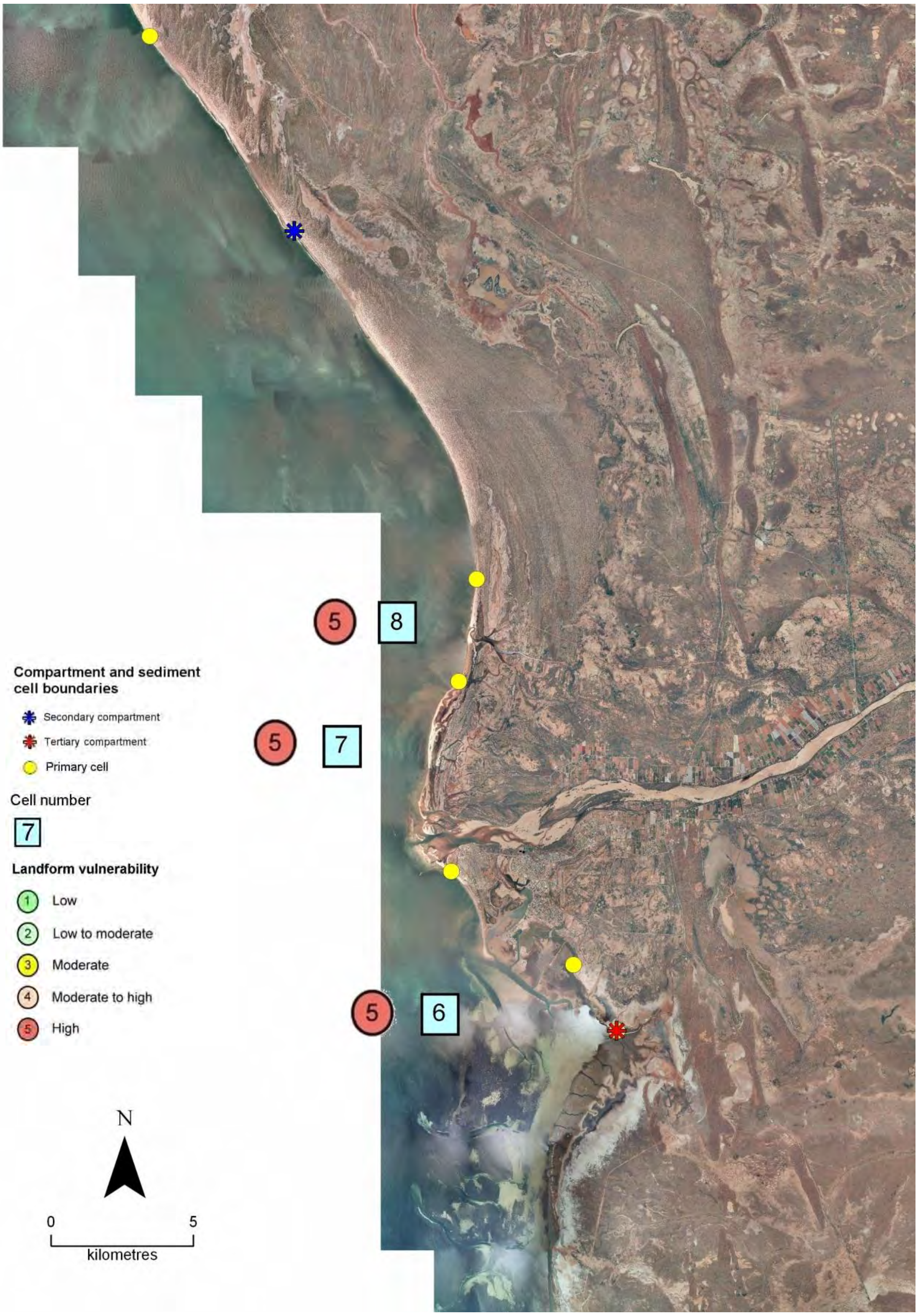

Figure G-7: Carnarvon Area Vulnerability

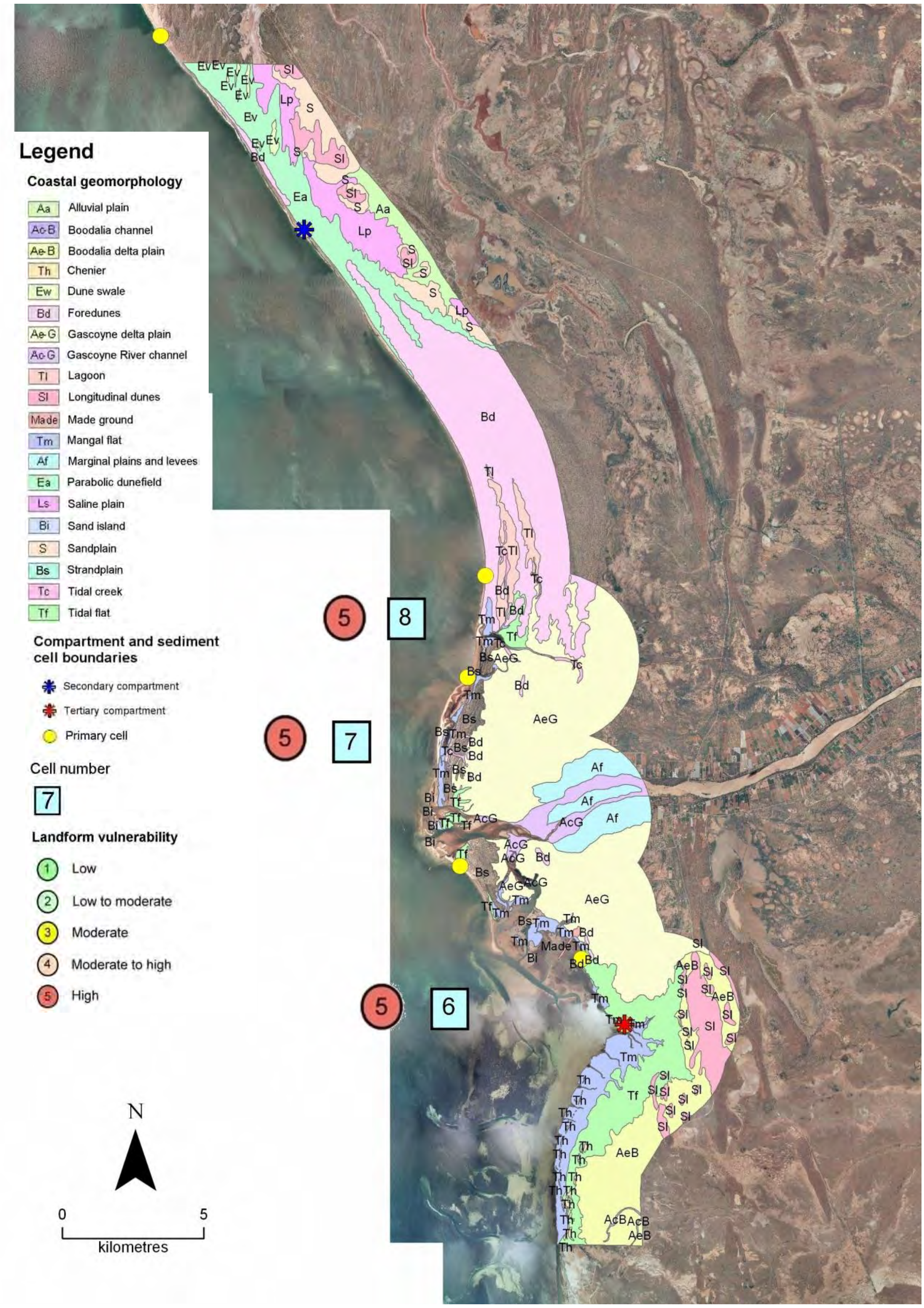

Figure G-8: Carnarvon Area Landforms

Table G-13: Landforms of the Carnarvon Area and their Relative Instability (After: Gozzard 2012). See Table2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Alluvial plain (Aa)	Nearly flat, saline alluvial plains, sluggish drainage tracts and prominent drainage foci, minor limestone outcrop plains and sandy banks; soils are red silts and clays.	Moderate
Boodalia channel (AcB)	50 m wide river bed, incised with steep banks, carrying bedloads of sand, bounded by very low levees with numerous fan-shaped crevasse splays.	High (Unstable)
Boodalia delta plain (AeB)	Flat plain of abandoned lobe of Gascoyne river, extensive deflated areas of bare soil; soils are reddish brown silty sands to sandy clays.	Moderate
Chenier (Th)	Arcuate belts of discrete elongated shell and sand spits and low beach ridges parallel to the coast, stranded on the coastal mudflats and mangal flats at the seaward edge of Boodalia delta plain.	High (Unstable)
Foredunes (Bd)	Low undulating plains composed of numerous parallel individual low foredune ridges rarely exceeding 5m in height; soils are pink or light brown loose calcareous sands.	High (Unstable)
Gascoyne delta plain (AeG)	Lobate flat plain extending about 7 km either side of the Gascoyne River; soils are homogeneous red brown mud and sandy muds.	Moderate
Gascoyne River channel (AcG)	Single, low sinuosity river channel with an average width of 600 m with bedloads of quartz sand and gravel.	High (Unstable)
Interdune flat (Ev)	Interdunal corridors in parabolic dunefield with undulating calcareous sandy floors.	Moderate
Lagoon (Tl)	Flat, restricted plains with silty clay soils, enclosed or partly enclosed by barrier deposits, intergrading with tidal flats.	High (Unstable)
Longitudinal dunes (Sl)	Linear dunes, mostly single and orientated north-south with up to 15 m relief; soils are red sands.	Moderate
Made ground (Made)	Man-made or artificial ground.	Moderate
Mangal flat (Tm)	Flat to gently inclined surface vegetated by dense thickets of *Avicennia marina* up to 4 m high on an organic-rich muddy substrate.	High (Unstable)
Marginal plains and levees (Af)	Raised sandy banks and marginal plains with undulating surfaces; very irregular in plan, varying in width from 400 m to over 3.5 km; individual levee deposits form ribbons of silt and fine sand up to 10 m in thickness; height of levees varies from 3-5 m above adjacent areas.	Moderate
Parabolic dunefield (Ea)	Large or very large long-walled parabolic dunes, relief mainly 30-60 m; soils are non-coherent light brown or pink calcareous sands.	Moderate
Saline flat (Lp)	Flat plains; soils are highly saline and gypsiferous.	High (Unstable)
Sand island (Bi)	Supratidal hummocks of sand as littoral islands at the mouth of the Gascoyne River; formed of single or multiple sand spits; soils are shelly sands.	High (Unstable)
Sandplain (S)	Undulating sandy plain, locally lightly mantled with limestone gravel; slopes <0.5%; soils are yellowish red to dark red sands.	Low (Stable)
Strandplain (Br)	Seaward edge of Gascoyne Delta; up to 1 km wide, thin to thick bedded sand with minor muddy sand comprising beach, beach ridge, tidal flat and supratidal flat depositional areas.	High (Unstable)
Tidal creek (Tc)	Tidal water muddy drainage channel incising tidal flats.	High (Unstable)
Tidal flat (Tf)	Supratidal infrequently inundated halophyte mudflats at seaward edges of Gascoyne and Boodalia Delta plains; Boodalia Delta plain has an ordered pattern of tidal creeks radial to the coast; Gascoyne Delta plain tidal flats are part of the strandplain sequence; soils are silts and clays.	High (Unstable)

Table G-14: Carnarvon Area Sediment Cell Description

Cell	S	N	INSHORE	SHORE	BACKSHORE
8	Gascoyne River North	Miaboolya Beach	The cell is part of the northern flank of the Gascoyne River delta; hence the offshore area includes the subaqueous deltaic plain and prodelta slope leading down to it.	The W-facing sandy shore is formed by a chenier spit and foredune ridge complex. The centre of the spit complex has been breached by a large tidal creek linked to the surface drainage system further landward. The sandy beach along the chenier is moderately exposed and has a reflective profile.	The barrier is an active chenier spit and dune ridge. Away from the mouth of the tidal creek the foredune on the chenier is discontinuous and has a 25 to 50% vegetation cover. There is 50-75% vegetation cover on the foredune ridges and landward. The backshore deltaic environment includes cheniers, beach ridges, supratidal and intertidal flats, tidal creeks, runoff channels, palaeochannels and shallow basin swamps.
7	Gascoyne River South	Gascoyne River North	This cell includes the active river mouth and delta of the Gascoyne River, the offshore area of the subaqueous deltaic plain and prodelta slope leading down to it.	Away from the river mouth with its channels and shoals, the shore is a seawardly convex chenier spit complex. The sandy beach along the chenier is moderately exposed and has a reflective profile.	The barrier is an active chenier spit and dune ridge with washover fans encroaching tidal flats and tidal creeks. In places the spit has a 25 to 50% vegetation cover, but much of it is bare sand and has been subjected to overwash during storms. The backshore deltaic environment includes cheniers, beach ridges, supratidal and intertidal flats, tidal creeks, runoff channels, palaeochannels and shallow basin swamps.
6	Massey Bay	Gascoyne River South	Part of the the active delta of the Gascoyne River is located in this cell. Hence the offshore area includes the subaqueous deltaic plain. Although the SE part of the cell west of the entrance to the Facine has been substantially modified by engineering works the nearshore seabed includes intertidal flats and a runoff channel linked to tidal creeks.	The SW-facing shoreline between Massey Bay and the Facine entrance includes tidal flats and a mangal varying in width from approximately 100m to 500m. The northern section of the cell includes the Babbage Island spit which is over 2km long, as well as an older recurved or washover feature at Pelican Point. Beaches along the spit are moderately exposed and have a reflective profile.	In the northwestern part of the cell the barrier is comprised of a low-lying chenier and beach ridge plain that is fronted on its seaward margin by a moderately high frontal dune ridge. The foredunes and frontal dunes along the Babbage Island spit have been extensively scarped. The moderately-high frontal dunes washed over by storm surge in recent events and the spit breached in two places; one close to its proximal end, the other midway between Pelican Point and the distal end of the spit.

Table G-15: Carnarvon Area Sediment Cell Susceptibility, Instability & Vulnerability Rankings

Sediment Cell	Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
8	Gascoyne River North to Miaboolya Beach	5	5	5	5	20	**H**	5	3	4	3	15	**H**	5	**H**
7	Gascoyne River South to Gascoyne River North	5	5	5	5	20	**H**	5	3	5	5	18	**H**	5	**H**
6	Massey Bay to Gascoyne River South	5	5	5	5	20	**H**	5	3	4	4	16	**H**	5	**H**

Table G-16: Carnarvon Area Sediment Cell Susceptibility, Instability and Vulnerability Rankings and Implications

Susceptibility and Instability Rankings should not be used independently.

No.	Cell	From Long.	From Lat.	To Long	To Lat.	Susceptibility		Instability		Vulnerability		
						Rank	Implications	Rank	Implications	Rank	Risk	Rationale
8	Gascoyne River North to Miaboolya Beach	113.629	-24.8197	113.6345	-24.7871	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.
7	Gascoyne River South to Gascoyne River North	113.6276	-24.8801	113.629	-24.8197	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.
6	Massey Bay to Gascoyne River South	113.6707	-24.9089	113.6276	-24.8801	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.

Appendix G5 Quobba-Blowholes Area

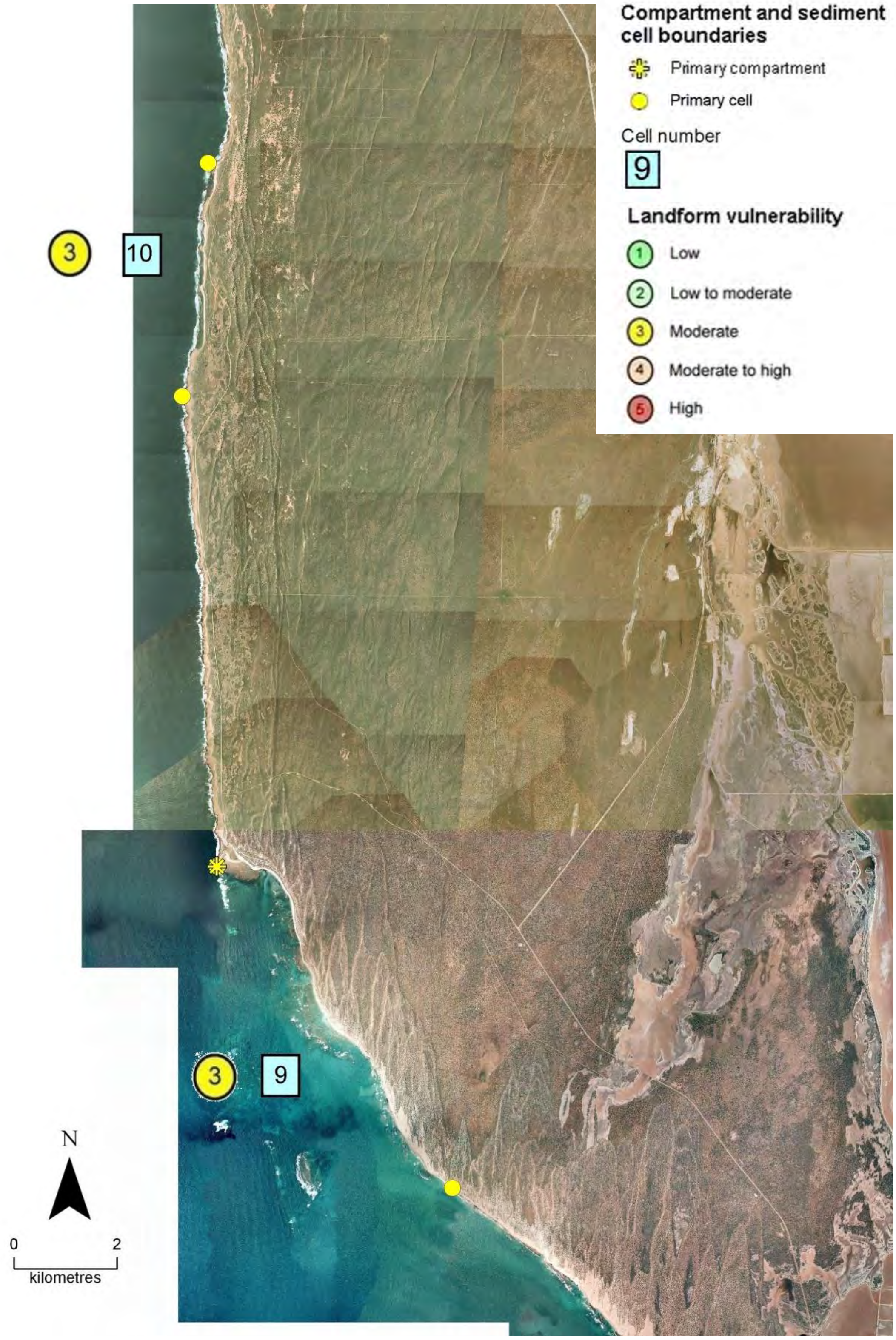

Figure G-9: Quobba-Blowholes Area Vulnerability

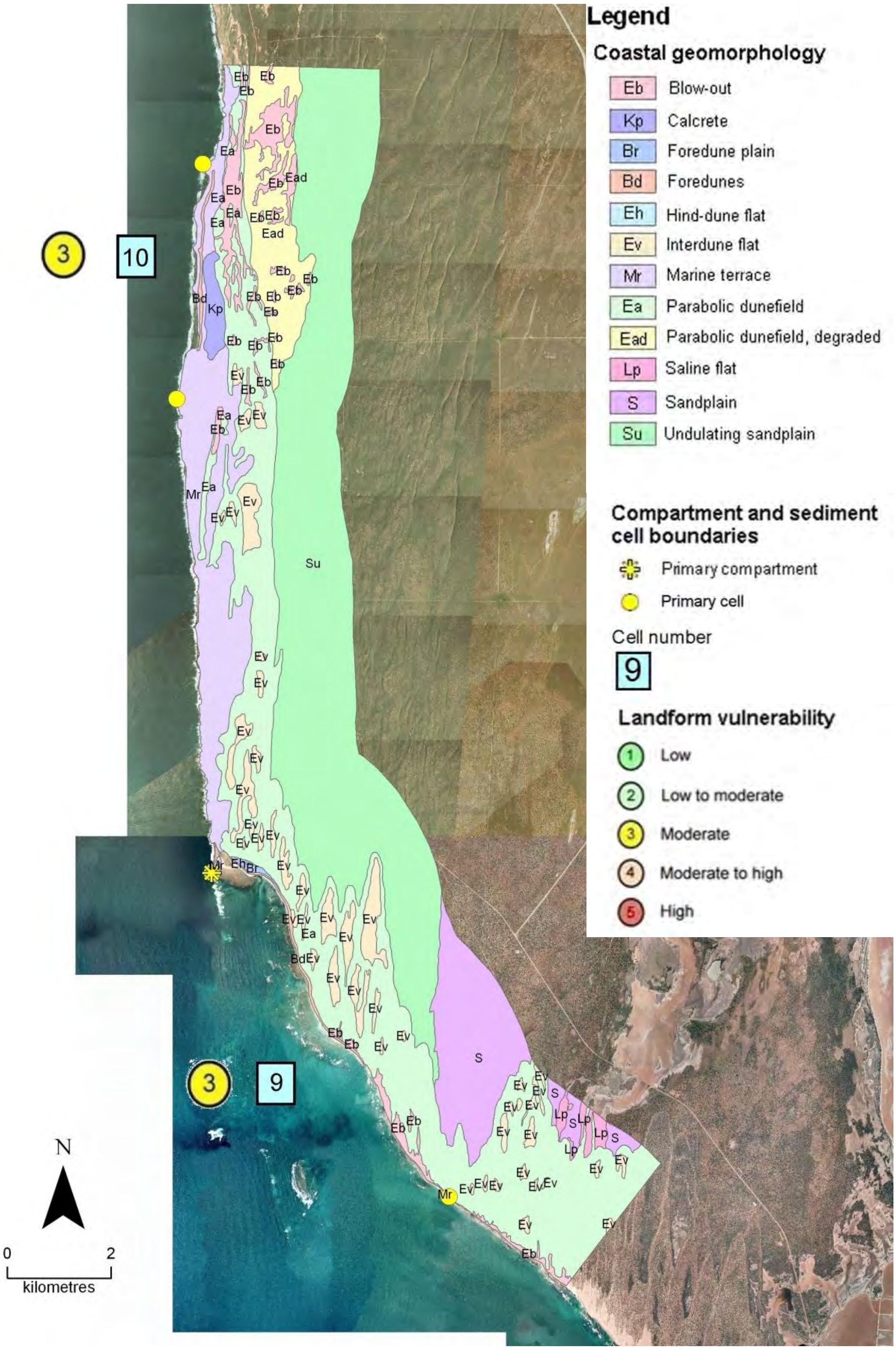

Figure G-10: Quobba-Blowholes Area Landforms

Table G-17: Landforms of the Quobba-Blowholes Area and their Relative Instability (After: Gozzard 2012). See Table2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Blow-out (Eb)	Isolated active parabolic dunes with arcuate crests and steep north-facing slopes; soils are loose light brown or pink calcareous sands.	High (Unstable)
Calcrete (Kp)	Isolated outcrop of pedogenic calcrete at Quobba Station developed on Bundera Calcarenite of Last Interglacial age.	Low (Stable)
Foredune plain (Br)	Low undulating plain at the Point Quobba shack settlement composed of several parallel individual low foredune ridges rarely exceeding 5m in height; soils are pink or light brown loose calcareous sands.	Moderate
Foredunes (Bd)	Relatively narrow shore-parallel fringe comprising one or two low ridges of pink to light brown loose calcareous sand.	High (Unstable)
Hind-dune flat (Eh)	300 m long, narrow, flat, stable area between the foredune plain and parabolic dunefield at the Point Quobba settlement; soils are non-coherent sands.	Moderate
Interdune flat (Ev)	Interdunal corridor in parabolic dunefield with undulating calcareous sandy floor.	Moderate
Marine terrace (Mr)	Outcrops of Bundera Calcarenite of Last Interglacial age as a raised marine terrace and low cliffs north of Point Quobba.	Low (Stable)
Parabolic dunefield (Ea)	Large or very large stabilised long-walled parabolic dunes, relief mainly 30-60 m; soils are non-coherent light brown or pink calcareous sands.	Moderate
Parabolic dunefield, degraded (Ead)	Large or very large long-walled parabolic dunes, relief mainly 30-60 m; degraded landforms represent an older stabilised dune system; soils are non-coherent light brown or pink calcareous sands.	Moderate
Saline flat (Lp)	Flat plain of the extreme southern end of Lake MacLeod; soils are highly saline and gypsiferous; subject to ponding and inundation by alluvial and diluvial processes.	High (Unstable)
Sandplain (S)	Flat to gently undulating sandy plain, locally with longitudinal dunes; soils are yellowish red to dark red sands soils.	Low (Stable)
Undulating sandplain (Su)	Undulating sandy plain with linear to reticulate, north-trending dunes; soils are red to brown sands.	Low (Stable)

Table G-18: Quobba-Blowholes Area Sediment Cell Description

Cell	S	N	INSHORE	SHORE	BACKSHORE
10 (2ndary)	Quobba Station South	Quobba Station North	Exposed rocky coast occurs between Point Quobba and Red Bluff. Along the coast between Quobba Station South and Quobba Station North the inshore waters are deep, commonly >5m and the seabed is rocky.	In plan, the shoreline includes four shallowly embayed beaches separated by cliffed supratidal and intertidal platforms. The W facing beaches are perched on a rocky intertidal platform, commonly immediately seaward of a partially buried bluff in the supratidal platform. The beaches are exposed and have reflective profiles.	Long walled parabolic dunes sourced from beaches south of Point Quobba overlie the sandstone topography. The seaward margin of this perched barrier, close to its junction with the exposed supratidal platform, has been reworked by onshore winds, surface run off and perhaps wave action. A narrow foredune ridge is located along the backshore.
9	Fitzroy Reefs	Point Quobba	The area between Fitzroy Reefs and Point Quobba is the downdrift end of the Miaboolya strand plain. The seabed of the inner shelf, close to shore includes outcrops of shallow intermittent reef or broken pavement in water depths <10m.	The coast faces SW and has an irregular or rhythmic shore with low-amplitude salients in the lee of reef outcrops. The exposed beach is mainly perched on sub-tidal platform. It is nearly continuous with one or two rocky cliffs outcropping at the shore. The largest cliffs are those outcropping at Point Quobba. Beach morphology includes relective and transitional profile forms.	An episodic transgressive barrier is present along much of the coast. The foredunes are commonly scarped or absent. South of the camping area at Quobba the foredunes have <25% vegetation cover. In places the frontal dunes have been scarped. Active blowouts and mobile sand sheets are apparent with vegetation cover between 50 and 75%. A narrow foredune plain with a discontinuous, but moderately high, foredune ridge has formed in the lee of reefs and the island at Point Quobba. This low-lying land abuts truncated parabolic dunes to landward.

Table G-19: Quobba-Blowholes Area Sediment Cell Susceptibility, Instability & Vulnerability Rankings

Sediment Cell	Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
10 (2°)	Quobba Station South to Quobba Station North	3	3	3	2	11	**M**	2	3	4	3	12	**M**	3	**M**
9	Fitzroy Reefs to Point Quobba	3	3	2	4	12	**M**	2	4	4	3	13	**M**	3	**M**

Table G-20: Quobba-Blowholes Area Sediment Cell Susceptibility, Instability and Vulnerability Rankings and Implications

Susceptibility and Instability Rankings should not be used independently.

No.	Cell	From Long.	From Lat.	To Long	To Lat.	Susceptibility		Instability		Vulnerability		
						Rank	Implications	Rank	Implications	Rank	Risk	Rationale
10 (2ndary)	Quobba Station South to Quobba Station North	113.3996	-24.4083	113.4039	-24.3673	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
9	Fitzroy Reefs to Point Quobba	113.4542	-24.5466	113.4079	-24.4909	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.

Appendix G6 Gnaraloo Area

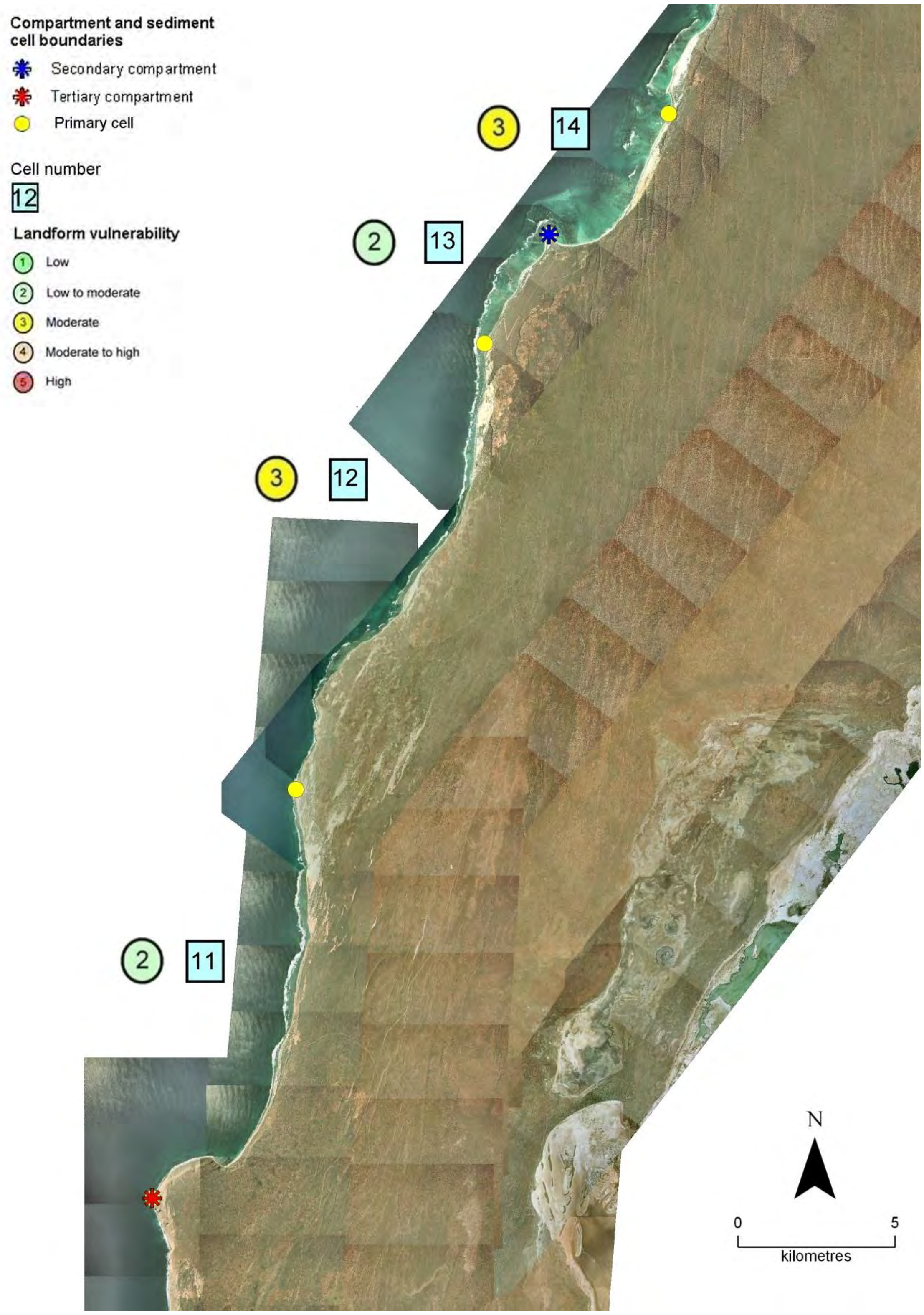

Figure G-11: Gnaraloo Area Vulnerability

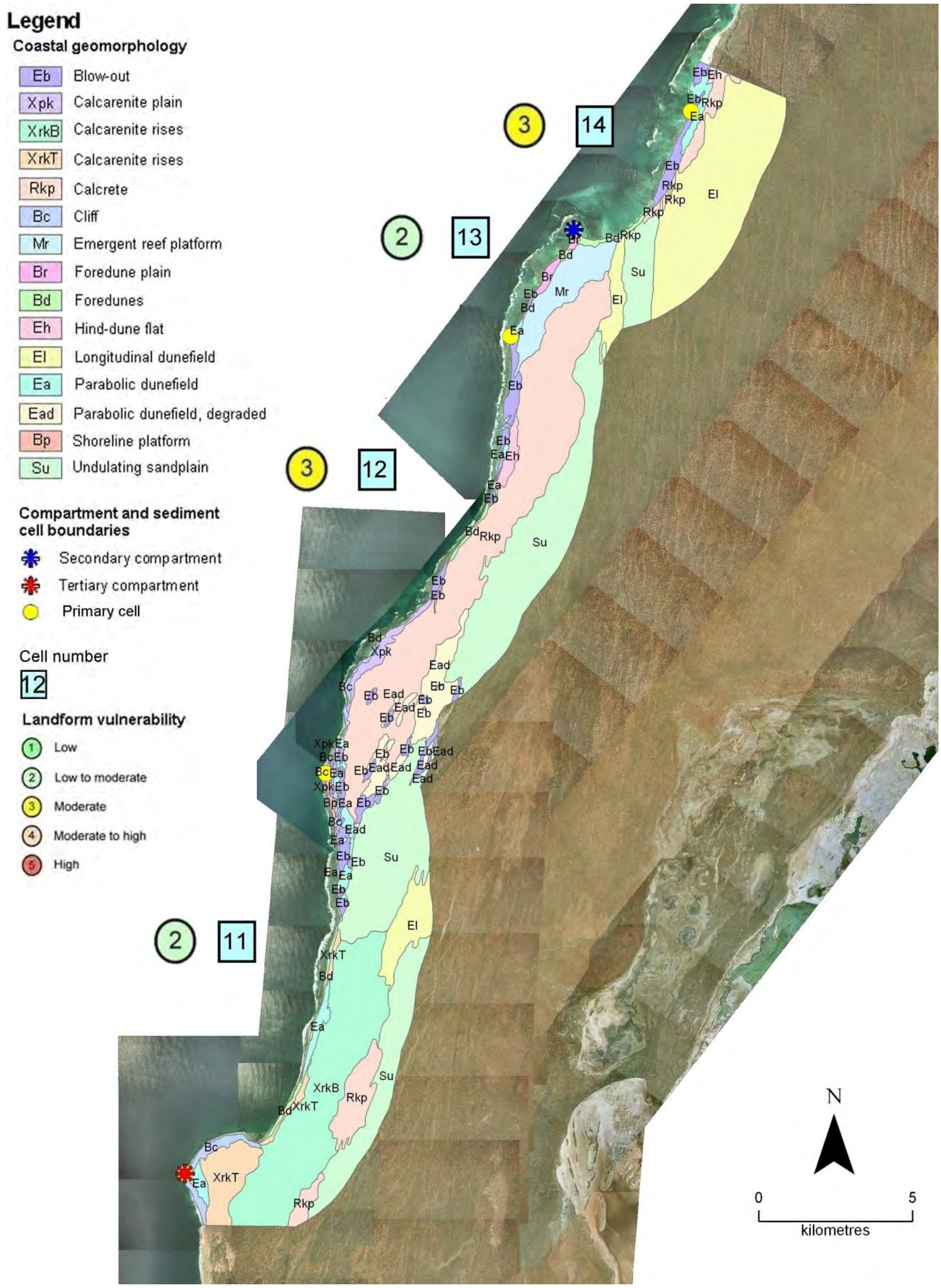

Figure G-12: Gnaraloo Area Landforms

Table G-21: Landforms of the Gnaraloo Area and their Relative Instability (After: Gozzard 2012). See Table2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Blow-out (Eb)	Active parabolic dunes with arcuate crests and steep northeast-facing slopes; soils are loose light brown or pink calcareous sands.	High (Unstable)
Calcarenite plain (Xpk)	Narrow, undulating coastal plains with rocky ridges and outcrops of limestone; developed on Trealla Limestone and Bundera Calcarenite; densely mantled with limestone pebbles or cobbles; soils are shallow alkaline sands.	Low (Stable)
Calcarenite rises (XrkB)	Irregular limestone ridges and rises; developed in Bundera Calcarenite; densely mantled with limestone pebbles and cobbles; original dune shapes are mostly preserved; soils are calcareous reddish brown to yellow sands.	Low (Stable)
Calcarenite rises (XrkT)	Undulating limestone rises and plains; developed in Trealla Limestone; soils are shallow reddish brown sands with stony outcrops.	Low (Stable)
Calcrete (Rkp)	Outcrops of pedogenic calcrete developed on Bundera Calcarenite of Last Interglacial age; soils are shallow sandy soils over calcrete with occasional small stony outcrops.	Low (Stable)
Cliff (Bc)	Steep coastal cliffs and cliff tops developed in Trealla Limestone and Giralia Calcarenite.	Moderate
Emergent reef platform (Mr)	Continuous coastal plain as a raised shoreline terrace up to 1 km in width, rising to about 1 m above modern high water mark; occupied by Bundera Calcarenite; Last Interglacial in age; comprises indurated calcarenite and coralgal deposits containing shells and coral debris representing a former fringing reef and associated lagoonal deposits.	Low (Stable)
Foredune plain (Br)	Low undulating plains between Gnaraloo Homestead and Gnaraloo Bay composed of several parallel individual low foredune ridges rarely exceeding 5m in height; soils are pink or light brown loose calcareous sands.	Moderate
Foredunes (Bd)	Relatively narrow shore-parallel fringe comprising one or two low ridges of pink to light brown loose calcareous sand.	High (Unstable)
Hind-dune flat (Eh)	Long, narrow, flat, stable areas between the coastal dunes and the calcrete escarpment; soils are non-coherent sands.	Low (Stable)
Longitudinal dunefield (El)	Linear to reticulate dunes up to 15 m above the surrounding sandplain; soils are red to dark red siliceous sands.	Moderate
Parabolic dunefield (Ea)	Large or very large stabilised long-walled parabolic dunes, relief mainly 30 m; soils are non-coherent light brown or pink calcareous sands.	Moderate
Parabolic dunefield, degraded (Ead)	Long-walled parabolic dunes, low relief, degraded landforms represent an older stabilised dune system; soils are non-coherent light brown or pink calcareous sands.	Moderate
Shoreline platform (Bp)	Flat to gently undulating rocky platform at the base of cliffs.	Moderate
Undulating sandplain (Su)	Undulating sandy plain with linear, north-trending dunes; soils are red to brown sands.	Low (Stable)

Table G-22: Gnaraloo Area Sediment Cell Description

Cell	S	N	INSHORE	SHORE	BACKSHORE
14	Gnaraloo Bay South	Gnaraloo Bay North	Due to a change in orientation of the coast there is a gap in the fringing reef which is further offshore and deeper in this cell. It again closes with the coast near Gnaraloo Bay North. The inshore lagoonal waters are <5m deep and the seabed includes patches of reef and sand, with an increasing proportion of intermittent reef and lagoonal pavement with distance along the coast.	Gnaraloo Bay is a zeta-form bay. The deeply indented southern section faces N to the break in the fringing reef. The straight section of shore faces NW and is rejoined by fringing reef. The beach is continuous. Its profile changes from a flat profile in the sheltered NW flank of the cuspate foreland to more exposed reflective and transitional forms with distance around the bay. However, the proportion of beach perched on beachrock ramps also increases to the northeast.	The cell has a narrow, receded or mainland barrier form away from the foredune ridges that comprise the cuspate foreland. A narrow, moderately high (5 to 10m) foredune ridge abuts and overlies an older sandplain surface. The seaward face of the foredune ridge is increasingly steep and becomes more discontinuous and scarped with distance north. The ridge also widens from <50m to approximately 400m in the lee of the fringing reef. Much of the wider ridge complex is a bare sand sheet.
13	Gnaraloo North	Gnaraloo Bay South	The fringing reef and the shallow lagoon it encloses widens from approximately 300m at Gnaraloo North (near the airstrip) to 600m two thirds the way along the coast. It is approximately 400m wide off the cuspate foreland at Gnaraloo Bay South.	Much of the continuous beach is perched on a beachrock ramp or a rocky sub-tidal pavement. It is sheltered by the fringing reef and has a rounded or reflective profile.	A foredune ridge is present along the southern half of the cell but becomes discontinuous and scarped with distance north. The ridge is backed to landward by a series of high ridges suggestive of a receded barrier. Deflation hollows between some ridges indicate they overlay an older sandplain surface. Vegetation cover on the dune complex is highly varied but is mainly between 50 and 75%. An active parabolic dune is in the centre of the cuspate foreland at the northern end of the cell.
12	Gnaraloo South	Gnaraloo North	The seabed close to shore is deep (>5m), rocky and with reef outcrops and broken pavement apparent. An extensive fringing reef platform exists close to shore. It ranges in width up to approximately 450m between the shoreline and the seaward margin of the platform.	North of the high cliffs and adjoining fringing reef, the NW facing shoreline has a shallowly-indented arcuate plan form. A continuous sandy beach is perched: on the sub-tidal platform; on intertidal platform and separated from it in places by a shallow inshore lagoon; on beachrock; or above a low bluff fronting a supratidal platform. The exposed beach is partially protected by the sub-tidal platform and commonly has a reflective profile.	The southern half of the cell has a rocky shore with a limited area of dune development on its NW facing shore. This changes with aspect along the coast such that a perched, episodic transgressive dune system occurs on the mainly W facing shore in the northern third of the embayment.
11	Red Bluff	Gnaraloo South	The greater proportion of seabed close to shore is rocky, with reef outcrops and broken pavement apparent. An extensive sub-tidal to intertidal reef platform exists close to shore. It varies in extent and is narrowest in the southern sector of the cell but ranges up to approximately 600m width between the shoreline and its seaward margin in the northern third.	The WNW facing shoreline has a shallowly-indented arcuate plan form. A continuous sandy beach is perched: on the sub-tidal platform; on intertidal platform and separated from it in places by a shallow inshore lagoon; on beachrock; or above a low bluff fronting a supratidal platform. The exposed beach is partially protected by the sub-tidal platform and commonly has a reflective profile.	At the southern end of the cell a 150 to 250m wide colluvial apron falls from the Trealla Limestone bluffs to a supratidal platform around the headland. With distance north the colluvial apron widens and a barrier of episodic dunes is perched on the supratidal platform. Active blowouts, nested parabolic dunes and mobile sand sheets are common in the northern third of the cell. The foredune ridge and other dunes are discontinuously distributed along the coast.

Table G-23: Gnaraloo Area Sediment Cell Susceptibility, Instability & Vulnerability Rankings

Sediment Cell	Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
14	Gnaraloo Bay South to Gnaraloo Bay North	3	4	3	4	14	**M**	2	3	3	3	11	**M**	3	**M**
13	Gnaraloo North to Gnaraloo Bay South	1	3	2	4	10	**M**	1	2	3	2	8	**L**	2	**L-M**
12	Gnaraloo South to Gnaraloo North	1	2	3	4	10	**M**	2	2	3	3	10	**M**	2	**M**
11	Red Bluff to Gnaraloo South	3	2	3	1	9	**L**	3	3	4	4	14	**M**	2	**L-M**

Table G-24: Gnaraloo Area Sediment Cell Susceptibility, Instability and Vulnerability Rankings and Implications

Susceptibility and Instability Rankings should not be used independently.

No.	Cell	From	From	To Long	To Lat.	Susceptibility		Instability		Vulnerability		
						Rank	Implications	Rank	Implications	Rank	Risk	Rationale
14	Gnaraloo Bay South to Gnaraloo Bay North	113.5413	-23.7641	113.5779	-23.7287	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
13	Gnaraloo North to Gnaraloo Bay South	113.5216	-23.7957	113.5413	-23.7641	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
12	Gnaraloo South to Gnaraloo North	113.4651	-23.925	113.5216	-23.7957	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
11	Red Bluff to Gnaraloo South	113.4225	-24.0432	113.4651	-23.925	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.

Appendix G7 Coral Bay

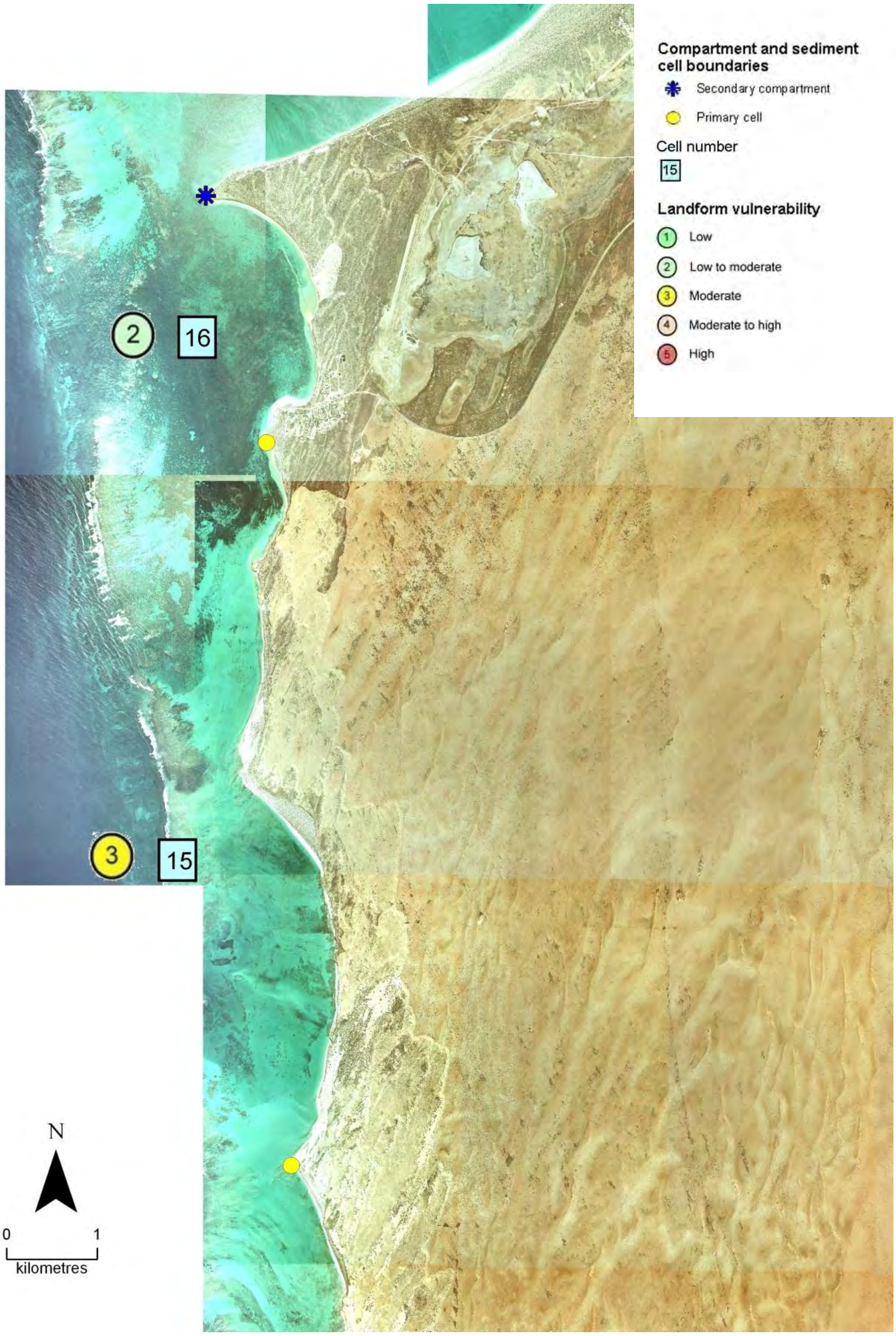

Figure G-13: Coral Bay Vulnerability

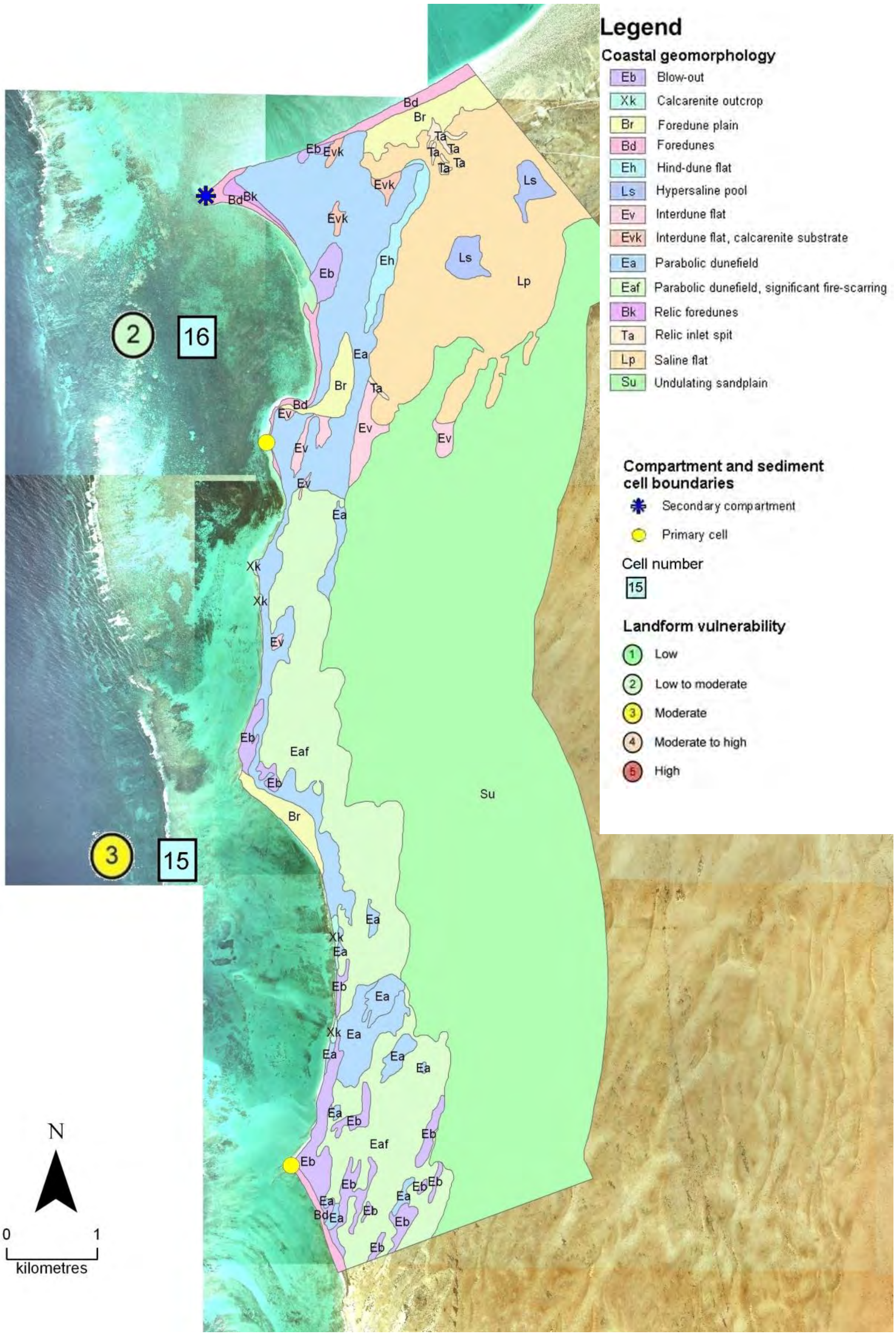

Figure G-14: Coral Bay Landforms

Table G-25: Landforms of the Coral Bay Area and their Relative Instability (After: Gozzard 2012). See Table2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Blow-out (Eb)	Isolated active parabolic dunes with arcuate crests and steep north-facing slopes; soils are loose light brown or pink calcareous sands.	High (Unstable)
Calcarenite outcrop (Xk)	Isolated small outcrops of Bundera Calcarenite of Last Interglacial age as shoreline platforms and low cliffs south of Coral Bay.	High (Unstable)
Foredune plain (Br)	Low undulating plains composed of numerous parallel individual low foredune ridges rarely exceeding 5m in height; soils are pink or light brown loose calcareous sands.	Moderate
Foredunes (Bd)	Relatively narrow shore-parallel fringe comprising one or two low ridges of pink to light brown loose calcareous sand.	High (Unstable)
Hind-dune flat (Eh)	2 km long, narrow, flat, stable area between the parabolic dunefield at Point Maud and the Cardabia saline flat; soils are non-coherent sands.	Moderate
Hypersaline pool (Ls)	Saline to hypersaline residual pools on the Cardabia saline flat, remnants of flood events.	High (Unstable)
Interdune flat (Ev)	Interdunal corridor in parabolic dunefield with undulating calcareous sandy floor.	Moderate
Interdune flat, calcarenite substrate (Evk)	Small interdunal depression in parabolic dunefield with flat calcarenite rock floor.	Moderate
Parabolic dunefield (Ea)	Large or very large long-walled parabolic dunes, relief mainly 30-60 m; stabilised by vegetation; soils are non-coherent light brown or pink calcareous sands.	Moderate
Parabolic dunefield, significant fire scarring (Eaf)	Large or very large long-walled parabolic dunes, relief mainly 30-60 m; bare soils devoid of vegetation by large-scale fire scarring; soils are non-coherent light brown or pink calcareous sands.	Moderate
Relic foredunes (Bk)	Backshore at Point Maud comprising a narrow, low undulating plain of several relic foredune ridges rarely exceeding 5 m in height; soils are pink or light brown loose calcareous sands	Moderate
Relic inlet spit (Ta)	Narrow, elongate inlet spits showing repeated patterns of accretion and breaching and detached distal portions; attached to stable barrier systems, erosion of which from wave action and tidal currents supplied the sediment that form the spits; formed within a tidal inlet system when the barrier was breached; spits are flood-orientated on both sides of the former inlet.	Moderate
Saline flat (Lp)	Flat plain; soils are highly saline and gypsiferous; subject to ponding and inundation by alluvial and diluvial processes; it is a palaeo-lagoon that was open to the sea in the vicinity of Mauds Landing during a period of higher sea level and formed by barring of the coastline by development of the Bateman Bay relic foredune plain.	High (Unstable)
Undulating sandplain (Su)	Undulating sandy plain with common linear to reticulate, northeast-trending, longitudinal dunes; residual windblown deposit developed on a substrate of Bundera Calcarenite of Last Interglacial age; soils are red to brown sands.	Low (Stable)

Table G-26: Coral Bay Sediment Cell Description

Cell	S	N	INSHORE	SHORE	BACKSHORE
16	Purdy Point	Point Maud	The coast between Purdy Point and Point Maud encompasses Coral Bay, a small embayment within Bills Bay which is landward of a break in the shallow platforms of Ningaloo Reef. The inshore waters of Bills Bay are shallow, generally <5m, and the seabed has >75% reef or pavement.	The WSW facing shore of the deeply arcuate Bills Bay has two smaller shallow embayments. The southern embayment is Coral Bay, with a NW facing shoreline. Its sheltered beach profile changes from a flat sandy beach on the northern flank of the Purdy Point foreland to a segmented form perched on beachrock to the northern, W-facing shore of the bay. The shore of the northern embayment faces SW on the southern flank of the large cuspate foreland at Point Maud. The beach is landward of a narrow lagoon formed by exposure of a line of beachrock in the inshore waters.	The cuspate foreland at Point Maud is comprised of high (>10m) episodic transgressive dunes, including long walled parabolic dunes and active blowouts. A low foredune plain forms the apex of the foreland. The foredune ridge is discontinuous and scarped in the vicinity of a mobile dune in the south of the small embayment. To the north it is continuous although steep-faced to seaward. The overall vegetation cover of the dune complex is between 50 and 75%
15	Point Anderson	Purdy Point	A nearly continuous section of the Ningaloo coral reef separates deep offshore waters from the shallow lagoonal waters inshore. The width of the lagoon varies from 1 to 2 km and is narrowest at the cell boundaries near Point Anderson and Purdy Point.	The W facing shoreline is irregular in plan with shoreline salients landward of the narrower section of the reef and a shallow embayment landward of the narrow gaps in the reef. The beach is discontinuous with sections separated by rocky headlands with low bluffs adjoining intertidal platforms. The sheltered beaches are commonly perched on intertidal beachrock ramps. These are backed by dunes with a scarped or steeply-faced seaward margin.	Old, episodic transgressive dunes are perched on a discontinuous bedrock surface. These have been truncated along the coast and the underlying limestone bedrock exposed along the shore. The modern dune ridge abuts the older dunes between the bedrock outcrops to form elements of a receded or mainland barrier. The dunes have a 50 to 75% vegetetion cover. Uncontrolled and ORV tracks are common in the cell, particularly immediately landward of the frontal dune ridge.

Table G-27: Coral Bay Sediment Cell Susceptibility, Instability & Vulnerability Rankings

Sediment Cell	Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
16	Purdy Point to Point Maud	1	5	3	4	13	M	1	2	3	2	8	L	2	L-M
15	Point Anderson to Purdy Point	1	5	2	4	12	M	2	3	3	2	10	M	3	M

Table G-28: Coral Bay Sediment Cell Susceptibility, Instability and Vulnerability Rankings and Implications

Susceptibility and Instability Rankings should not be used independently.

No.	Cell	From Long.	From Lat.	To Long	To Lat.	Susceptibility		Instability		Vulnerability		
						Rank	Implications	Rank	Implications	Rank	Risk	Rationale
16	Purdy Point to Point Maud	113.7663	-23.1462	113.7593	-23.1217	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
15	Point Anderson to Purdy Point	113.7705	-23.2183	113.7663	-23.1462	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.

Appendix G8 Vlamingh Head

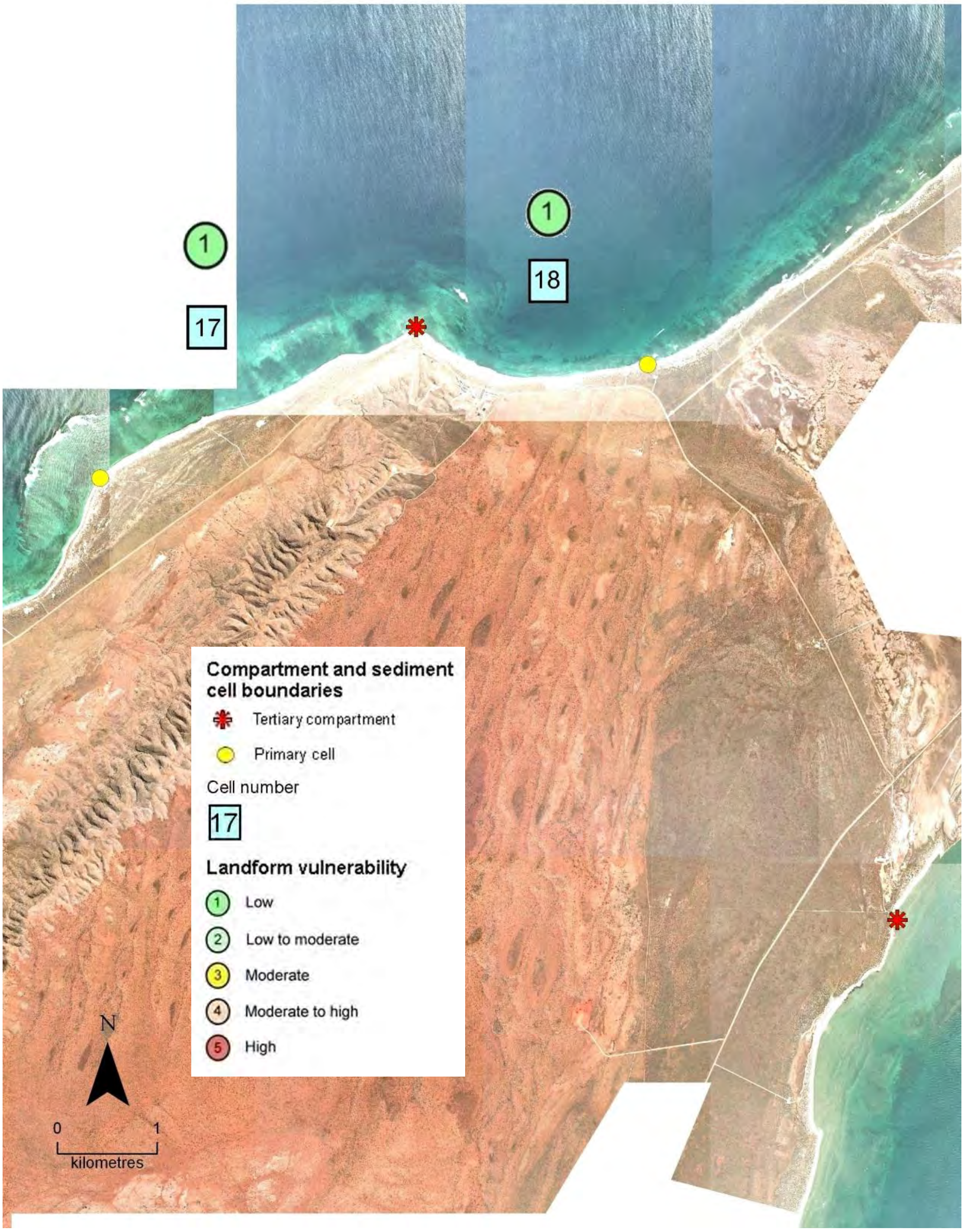

Figure G-15: Vlamingh Head Vulnerability

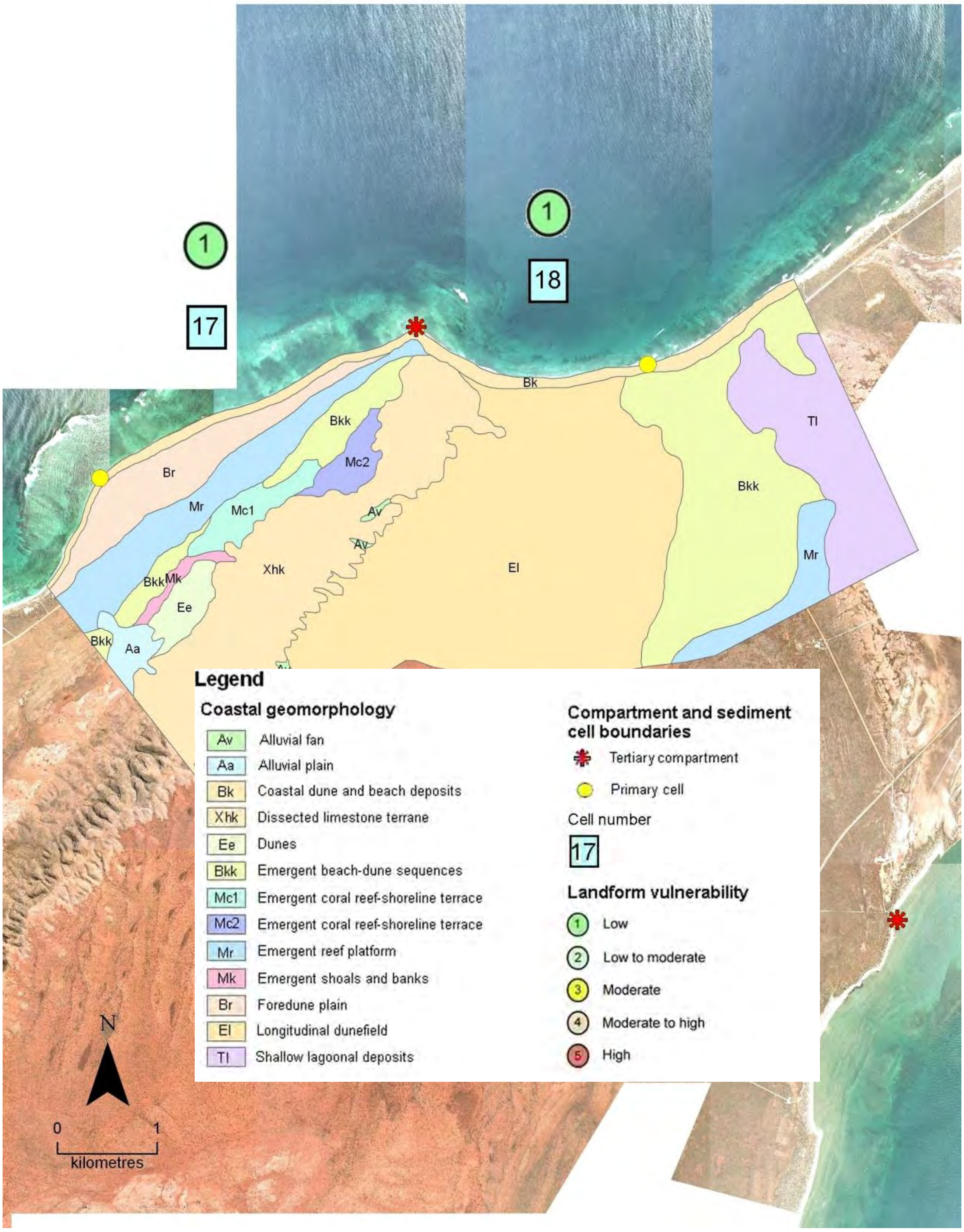

Figure G-16: Vlamingh Head Landforms

Table G-29: Landforms of the Vlamingh Head Area and their Relative Instability (After: Gozzard 2012). See Table2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Alluvial fan (Av)	Fan-conglomerate sequences deposited at the mouths of gorges; well entrenched at the fan head; the size of the fan is related to the catchment area of the associated stream; Last Interglacial to Mid-Holocene in age; sediments are dominated by limestone pebble- and cobble-sized conglomerates.	Moderate
Alluvial plain (Aa)	Nearly flat, sandy alluvial plains, occasionally gently undulating; soils are red to reddish brown sands and loamy sands with calcareous inclusions throughout the profile.	Moderate
Coastal dune and beach deposits (Bk)	Relatively narrow shore-parallel dune-beach fringe comprising one or two major dune ridges of pink to light brown loose sands.	High (Unstable)
Dissected limestone terrain (Xhk)	Erosional surfaces of 250-300 m relief; residual summits, hills and ridges with steep footslopes; high density dendritic drainage; developed in limestones of the Tulki Limestone.	Low (Stable)
Dunes (Ee)	Restricted area of well sorted, medium grained, large-scale, cross-bedded quartzose calcarenite with calcrete soils; eolian and minor shallow marine deposits of Pleistocene age developed in Exmouth Sandstone.	Low (Stable)
Emergent beach-dune sequences (Bkk)	West of Cape Range are extensive, relatively narrow ridges of fine- to coarse-grained bioclastic calcarenite of beach and dune sequences; dune shapes are mostly preserved; east of Cape Range is a broad area of coastal sediments with degraded dunes; Bundera Calcarenite of Last Interglacial age; moderate calcrete development.	Low (Stable)
Emergent coral reef-shoreline terrace (Mc1)	Emergent shoreline terrace overlain by deposits of coralgal reef limestone and coarse-grained carbonate-rich sandy sediments deposited in a back-reef lagoon; form the Tantabiddi Member of the Bundera Calcarenite of possible Pliocene age.	Low (Stable)
Emergent coral reef-shoreline terrace (Mc2)	Emergent shoreline terrace overlain by deposits of coralgal reef limestone and coarse-grained carbonate-rich sandy sediments deposited in a back-reef lagoon; form the Jurabi Member of the Bundera Calcarenite of possible Pliocene age.	Low (Stable)
Emergent reef platform (Mr)	Continuous coastal plain as a raised shoreline terrace up to 2.5 km in width, rising to about one 1 m above modern high water mark; occupied by the Tantabiddi Member of the Bundera Calcarenite; Last Interglacial in age; comprises indurated calcarenite and coralgal deposits containing shells and coral debris representing a former fringing reef and associated lagoonal deposits.	Moderate
Emergent shoals and banks (Mk)	Emergent shoals and banks with deposits of coarse-grained muddy calcarenite of the early Miocene Tulki Limestone.	Moderate
Foredune plain (Br)	Low undulating plain composed of numerous parallel individual low foredune ridges rarely exceeding 5m in height; soils are pink or light brown loose calcareous sands.	Moderate
Longitudinal dunefield (El)	Linear to reticulate dunes up to 25 m above the surrounding sandplain; Last Glacial Maximum in age and overlies Last Interglacial marine deposits; soils are red siliceous sands.	Moderate
Shallow lagoonal deposits (Tl)	Low-lying, flat saline plain subject to inundation and ponding by alluvial and diluvial processes; soils are highly saline and gypsiferous, brown to yellow loams and sands.	High (Unstable)

Table G-30: Vlamingh Head Sediment Cell Description

Cell	S	N	INSHORE	SHORE	BACKSHORE
18 (2ndary)	Vlamingh Head	East Vlamingh	Fringing coral reef continues along and close to the coast between Vlamingh Head and North West Cape. Although it is lower here than further south and the coast is more exposed. The inshore waters are shallow and the seafloor rocky. The rocky shoreface rises to a low bluff and undercut supratidal platlform extending continuously along the shore between Vlamingh Head and East Vlamingh (Surfers Beach East). A boulder beach sits on the platform and separates the bluffs from the foredunes to landward.	A rocky sandstone headland provides the control point for a zeta-form embayment facing NNW and extending from Vlamingh Head to North West Cape. The shore is rocky and the sandy beach and foredune ridge are perched on a supratidal platform cut in Exmouth Sandstone.	A discontinuoous foredune ridge is located along the backshore of the supratidal platform and boulder beach. It has 25 to 50% vegetation cover. Futher landward is a narrow ridge of perched dunes ridge with 50 to 75% vegetation cover. The ridge is comprised of nested blowouts and includes substantial areas of active dune.
17 (2ndary)	Babjarrimannos	Vlamingh Head	The Ningaloo coral reef is approximately 5 -500m offshore from the coast between Babjarrimannos and Vlamingh Head. It is separated from the shore by a shallow lagoon with intermittent reef and pavement covering much of the seabed. Closer to shore is a narrow strip of sand before the shoreface rises over an intertidal beachrock ramp.	Babjarrimannos is on the apex of a broad salient, 600m in depth, between the older sedimentary surface and the modern beach and extending over 4km along the coast south of Vlamingh Head. Its NW facing shoreline has an irregular, rhythmic form with smaller salients associated with inshore outcrops of rock. The continuous sandy beach is sheltered by the fringing reef and lagoon. It adjoins a foredune with a steep seaward face, has a segmented to reflective profile and is perched on beachrock.	The Babjarrimannos foreland is a foredune plain with a series of moderately high dune ridges. The modern foredune is discontinuous, subject to localised blowout and has a vegetation cover of <25%. Further landward the plain has a vegetation cover of 50 to 75% with the highest cover in swales between the ridges.

Table G-31: Vlamingh Head Sediment Cell Susceptibility, Instability & Vulnerability Rankings

Sediment Cell	Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
18 (2°)	Vlamingh Head to East Vlamingh	2	2	3	1	8	**L**	1	1	4	2	8	**L**	1	**L**
17 (2°)	Babjarrimannos to Vlamingh Head	1	2	1	4	8	**L**	1	2	3	2	8	**L**	1	**L**

Table G-32: Vlamingh Head Sediment Cell Susceptibility, Instability and Vulnerability Rankings and Implications

Susceptibility and Instability Rankings should not be used independently.

No.	Cell	From Long.	From Lat.	To Long	To Lat.	Susceptibility		Instability		Vulnerability		
						Rank	Implications	Rank	Implications	Rank	Risk	Rationale
18 (2ndary)	Vlamingh Head to East Vlamingh	114.1088	-21.8026	114.1312	-21.8056	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
17 (2ndary)	Babjarrimannos to Vlamingh Head	114.0785	-21.8168	114.1088	-21.8026	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.

Appendix G9 Exmouth

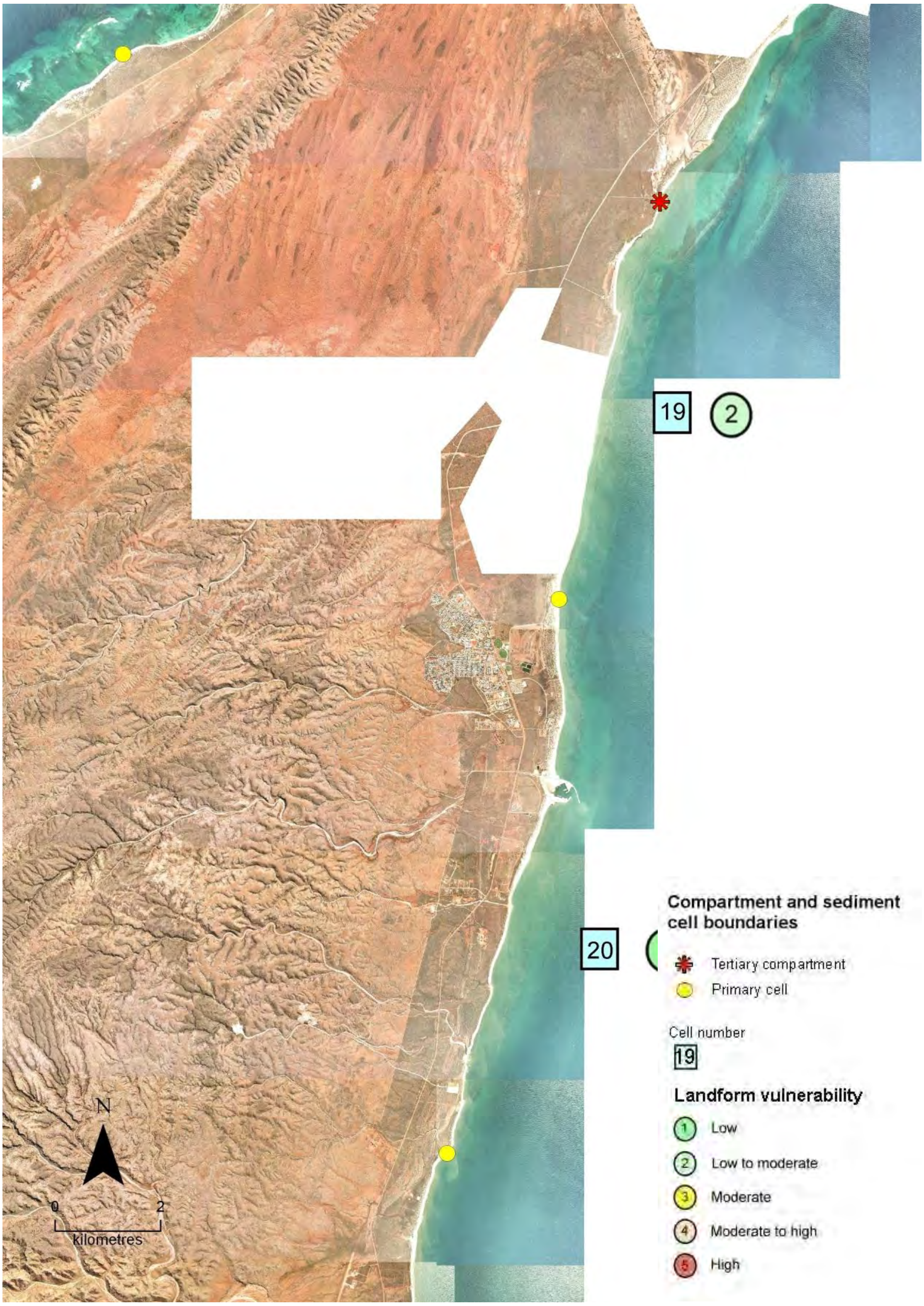

Figure G-17: Exmouth Vulnerability

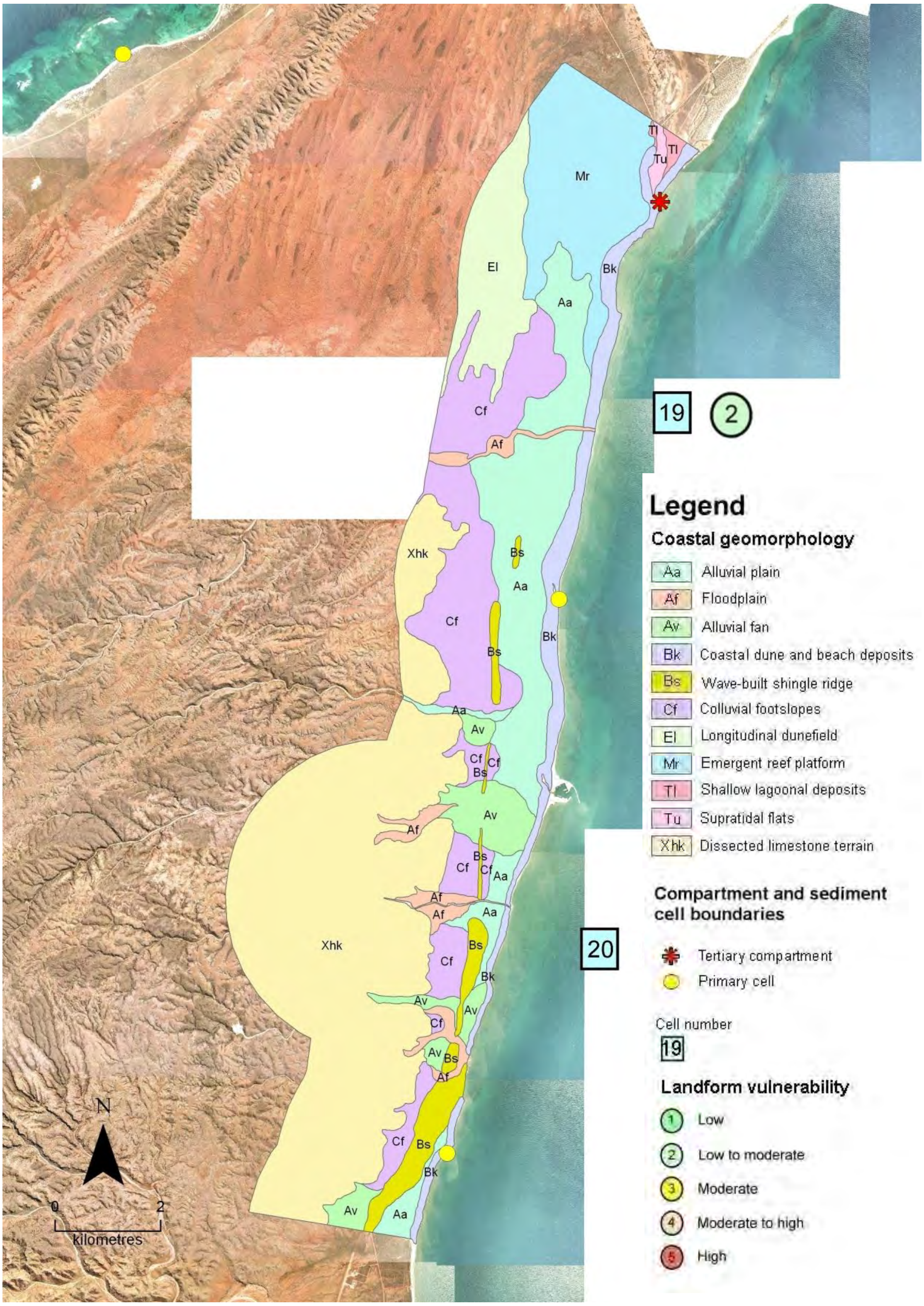

Figure G-18: Exmouth Landforms

Table G-33: Landforms of the Exmouth Area and their Relative Instability (After: Gozzard 2012). See Table2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Alluvial fan (Av)	Fan-conglomerate sequences deposited at the mouths of gorges; well entrenched at the fan head; the size of the fan is related to the catchment area of the associated stream; Last Interglacial to Mid-Holocene in age; sediments are dominated by limestone pebble- and cobble-sized conglomerates.	Moderate
Alluvial plain (Aa)	Nearly flat, sandy alluvial plains, occasionally gently undulating; soils are red to reddish brown sands and loamy sands with calcareous inclusions throughout the profile.	Moderate
Coastal dune and beach deposits (Bk)	Relatively narrow shore-parallel dune-beach fringe comprising one or two major dune ridges of pink to light brown loose sands; south of E	High (Unstable)
Colluvial footslopes (Cf)	Gentle footslopes below Cape Range; soils are sandy clays grading to medium clays, lightly to moderately mantled with limestone gravel and with limestone inclusions throughout the profile.	Moderate
Dissected limestone terrain (Xhk)	Erosional surfaces of 250-300 m relief; residual summits, hills and ridges with steep footslopes; high density dendritic drainage; developed in limestones of the Pilgramunna Formation, Trealla Limestone and Tulki Limestone.	Low (Stable)
Emergent reef platform (Mr)	Continuous coastal plain as a raised shoreline terrace up to 2.5 km in width, rising to about 1 m above modern high water mark; occupied by the Tantabiddi Member of the Bundera Calcarenite; Last Interglacial in age; comprises indurated calcarenite and coralgal deposits containing shells and coral debris representing a former fringing reef and associated lagoonal deposits.	Moderate
Floodplain (Af)	Inset alluvial fill occupying incised floodplains with steep banks, carrying bedloads of limestone pebbles and conglomerates.	Moderate
Longitudinal dunefield (El)	Linear to reticulate dunes up to 25 m above the surrounding sandplain; Last Glacial Maximum in age and overlies Last Interglacial marine deposits; soils are red siliceous sands.	Moderate
Shallow lagoonal deposits (Tl)	Low-lying, flat saline plain subject to inundation and ponding by alluvial and diluvial processes; soils are highly saline and gypsiferous, brown to yellow loams and sands.	High (Unstable)
Supratidal flats (Tu)	Isolated, unvegetated, low gradient tidal flat only inundated during extreme high tides and storm surge events; soils are calcareous silts and sands.	High (Unstable)
Wave-built shingle ridge (Bs)	Large shingle beach (bar) units as linear mounded ridges up to 8 m in height; comprises clast-supported gravel shingle with isolated lenses of coarse calcarenite of the Mowbowra Conglomerate Member of the Bundera Calcarenite.	Low (Stable)

Table G-34: Exmouth Sediment Cell Description

Cell	S	N	INSHORE	SHORE	BACKSHORE
20	Exmouth North	Qualing Pool	South of Exmouth the coast faces eastward into the central part of Exmouth Gulf. The 10m isobath is approximately 2km offshore. From there the shoreface rises to a broad platform, approximately 1km wide and with reef outcrops. A veneer of mixed sand and pebbles covers the platform close to shore. Rock outcrops as beachrock, platforms and undercut low bluffs along much of the shore.	The shoreline has small irregularities associated with rock outcrops and lithified deltaic sediments at stream mouths. The outcrops break the E facing coast into a series of small beaches. With distance south the beaches are increasingly comprised of mixed sand and pebbly sediments. The beaches are sheltered, commonly perched on beachrock, and have segmented to rounded profiles.	A single ridge of dunes comprised of nested blowouts parallels the coast, and is perched on a rock surface that is discontinuous and above high tide level. The ridge has been cut by several ephemeral streams known to carry a high discharge during cyclonic events. The dunes are of moderate height (5 to 10m) and have 50 to 75% vegetation cover. The foredunes along the beach are discontinuous, have a low vegetation cover, and in places are subject to ORV tracks along the coast.
19	Bundegi	Exmouth North	The coast south of Bundegi faces eastward into the northern waters of Exmouth Gulf. The 10m isobath is approximately 2.5km offshore. From there the shoreface rises to a broad rock platform, approximately 1km wide and with reef outcrops such as the inner and outer reefs at Bundegi. A thin veneer of mixed sand and pebbles partly covers the platform close to shore. Rock outcrops as beachrock along much of the shore.	With the exception of a shallow embayment containing a small tidal flat immediately south of Bundegi the shoreline is essentially straight, albeit with a slight rhythmic form. The sheltered E facing beach is perched on beachrock and has a segmented to rounded profile. It backs onto a foredune with a steep seaward face.	A single ridge of dunes parallels the coast, separating it from the low lying hinterland to landward. The dunes are of moderate height (5 to 10m) and have a 50 to 75% vegetation cover. The foredunes along the beach are discontinuous, predominantly mound dunes and have <25% vegetation cover.

Table G-35: Exmouth Sediment Cell Susceptibility, Instability & Vulnerability Rankings

Sediment Cell	Cell Boundaries	Nearshore Morphology	Shoreface Structure	Shoreline Shape & Orientation	Barrier, Deltas or Other Structures	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Morphology & Profile	Frontal Dune or Tidal Flats (Shoreline)	Barrier Vegetation or Tidal Flats (Surge)	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
20	Exmouth North to Qualing Pool	1	2	1	1	5	L	2	1	3	2	8	L	1	L
19	Bundegi to Exmouth North	1	2	1	1	5	L	2	1	2	5	10	M	2	L-M

Table G-36: Exmouth Sediment Cell Susceptibility, Instability and Vulnerability Rankings and Implications

Susceptibility and Instability Rankings should not be used independently.

No.	Cell	From Long.	From Lat.	To Long	To Lat.	Susceptibility		Instability		Vulnerability		
						Rank	Implications	Rank	Implications	Rank	Risk	Rationale
20	Exmouth North to Qualing Pool	114.1394	-21.9235	114.121	-22.0184	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
19	Bundegi to Exmouth North	114.1565	-21.8553	114.1394	-21.9235	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.