THE YALGORUP COAST:
BINNINGUP TO CAPE BOUVARD,
WESTERN AUSTRALIA

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for

Department of Planning
& Department of Conservation and Environment
Western Australia

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EXECUTIVE SUMMARY

The objective of this project was to describe the geomorphology of the Yalgorup Coast and identify areas of relative instability between Binningup and Cape Bouvard, including sections of the beach and barrier dune potentially subject to risk in response to projected environmental change.

Approach

The approach used follows overseas observations the inherited geologic framework plays a major role in determining barrier morphology, coastal cell evolution, and shoreface dynamics. Five sediment cells (Myalup, Lake Preston South, Preston Beach, Lake Clifton North and White Hills Road) are nested along the Yalgorup Coast and within a coastal compartment extending between Binningup and Cape Bouvard. In turn this coastal compartment is part of a large primary compartment extending from cape Naturaliste to Rottnest Island.

The hierarchy of coastal compartments and sediment cells on the Yalgorup Coast provides a spatial framework in which environmental change conveniently can be assessed for long-, medium- and short-term time scales. They have been used to structure identification of the geomorphology of the coast and nearshore waters as well as for comparative purposes to establish areas of relative instability.

At a geological scale, the primary coastal compartment has provided topographic control for formation of the Leschenault - Yalgorup Barrier as it evolved during the past 10,000 years. Barrier evolution is continuing at present as sediment is moved along and across the shore. Phases of dune activity associated with fluctuations in the intensity and duration of metocean processes continue to contribute to development of the dune ridge through the formation of foredunes, blowouts and nested parabolic sand dunes as the barrier migrates landwards.

Medium time scales are relevant to barrier changes occurring over decades and centuries. In this context, recurrence of the cycle of dune formation and migration on the Leschenault – Yalgorup Barrier is ultimately dependent on sediment supply from offshore and alongshore. At present the alongshore component of littoral sediment transport between Binningup and Cape Bouvard is critical to coastal stability and future evolution of the barrier. The ramifications of this are that the future medium-term stability of the Yalgorup Coast will potentially be affected by any updrift interference with the coastal sediment transport between Cape Naturaliste and Cape Bouvard as well as by natural variability and change to metocean processes.

At sub-decadal time scales, interaction of modern metocean processes with the inherited geologic framework has two ramifications. First, it produces localised reversals of the overall northerly littoral drift pattern. Alongshore variation in beach erosion, foredune formation and dune development occurs as a result of the interaction, with the most unstable reaches of coast in commonly in close proximity to shoreline salients and extensive rock outcrops. Second, it invalidates application of the Bruun Rule (Bruun 1988) that has been widely applied in the calculation of setback to development on mixed sandy and rocky coast in Western Australia (WAPC 2003).

Landforms

Three sets of Holocene dunes have been described foredunes, primary dunes and secondary dunes.

Low, discontinuous, hummocky dunes are common in the southern two cells (Myalup and Lake Preston South) in which the dune barrier is narrowest. They are higher in the Preston Beach cell (Cell 3) especially near the northern boundary where they have formed along the seaward margin of a large deflation basin. Foredune morphology is more variable in the northern cells, Lake Clifton North and White Hills Road. Some sections of the northern cells lack foredune and others landwards of rock platforms have erosion scarps. In contrast to the eroded foredunes, a narrow foredune plain is apparent as an inset at the southern end of the White Hills Road cell (Cell1).

Other dunal features of the barrier include fields of nested blowouts and/or parabolic dunes comprising the main ridge; coalescing blowouts where several mobile dunes are in the process of combining; mobile sand sheets where the combined dunes are moving freely as a single landform; and deflation basins which are extensive hollows remaining where sand sheets and/or coalescing blowouts have become detached from the shore. All are present as vegetated (stable) and unvegetated (mobile) forms.

Active blowouts and tracts of partially vegetated dunes, those with approximately less than 50% cover, occur in all sediment cells. The most extensive areas are landward of deflation basins in the northern sectors of Lake Preston South (Cell 4) and Preston Beach (Cell 3), on the southern flanks of the salients at the cell boundaries. Other active blowouts in the primary dunes occur close to beach access tracks in Cell 2 – Lake Clifton North as well as near the outlet of the Harvey Drain and as small individual or coalescing blowouts in Cell 5 – Myalup.

Coastal Change

Despite the lack of detailed morphostratigraphic and chronologic information, the following general observations about coastal change and stability can be summarised from the available data:

1. Bathymetry in Cells 4 and 5 (Lake Preston South and Myalup) has only a narrow section of shallow water (0 – 10 metres) before deepening to 10 – 20 metres. This coincides with the dominantly erosive environment immediately north of the rocky pavement off Binningup in the southern part of Cell 5 (Myalup).

2. Cells 1 and 2 (Myalup and Lake Preston South) have a broad area of shallow inshore water, coinciding with a more depositional inshore environment. The inshore waters of Cell 3 (Preston Beach) appear to be transitional with the narrow, shallow section of the southern cells beginning to deepen.

3. Comparison of changes to the vegetation line along the beach backshore from 1955 to 2006 indicate the coast between Binningup and Cape Bouvard is being eroded in the southern sector and accretion, albeit discontinuous, is more commonly occurring to the north. This is consistent with the prevailing SW winds, exposure to the SW swell regime and northerly littoral drift.

4. Although the barrier is widest in the northernmost cell (Cell 1 - White Hills Road), erosional features coincide with the rock platform occurring on the beach. Platforms and narrow inshore channels also coincide with the location of scarping or eroded foredunes elsewhere along the barrier.

5. Shoreline movement, indicated by changes to the vegetation line, in the two northern cells (Lake Clifton North and White Hills Road) is a reversal of the overall pattern between Binningup and Cape Bouvard, with the northern flank of salients undergoing accretion and the northern ends of the cells erosion. This is a short to medium term

process associated with localised migratory behaviour of sediment around the smaller salients under weak to moderate SW wind conditions, such as periods of prolonged sea breeze activity. It is also associated with higher landform variability than elsewhere along the barrier.

6. The deflation basin, a large erosional feature at the northern end of Cell 3 (Preston Beach) is located in a section with a prograding foredune and small localised blowouts (depositional features). This is apparently due to beach recovery following loss of sediment from the beach system but is consistent with the general erosional character of this part of the coast described in Point 5 above.
7. Stable and/or accreting foredunes occur dominantly in the northern half of the Yalgorup Coast; namely with sections in Cell 1 (White Hills Road) as well as along the southern half of Cell 2 (Lake Clifton North) and continuing into the northern part of Cell 3 (Preston Beach).

Observations of the Yalgorup coast over the historic period show that the coast responds to a range of coastal climate parameters, including sea level, wave direction and wave energy. These parameters are subject to considerable variability and uncertainty, both natural and anthropengenic and their effect is likely to be strongly influenced by exposure of the lithified basement which underlies the Leschenault-Yalgorup barrier.

Coastal climate variation over the historic period is generally larger than the predicted anthropogenic forcing over the next 30 years. Consequently, the natural variability may either mask or exacerbate the effects of climate-change induced trends, depending upon the active phase. Due to the apparent sensitivity of the Yalgorup coast to different coastal parameters, interpretation of the effects of climate variability, including anthropogenic change, should consider a range of possible scenarios, with variation of winds, wave conditions and water levels.

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1. OBJECTIVES & TASKS

The objective of this report is to identify areas of relative instability along the coast between Binningup and Cape Bouvard, including sections of the beach and barrier dune potentially subject to risk in response to projected environmental change.

1.1. TASKS

The following tasks were required in order to achieve the objective:

1. Describe the geomorphic components of the coast and Holocene barrier dune lands between Buffalo Road south of Binningup and Tim’s Thicket Road near Cape Bouvard, and extending seaward approximately from the western shore of Lake Preston to the 5 metre isobath;
2. Develop a conceptual model of coastal development during the Late Holocene based on the superficial geology and geomorphology, which is amenable to refinement by potential stratigraphic and chronologic investigation;
3. With particular reference to the ocean shore, determine landform changes in the period for which historical aerial photography and survey information is available; and
4. Relate the geomorphology to extant descriptions of groundwater hydrology and karst topography.

1.2. PROCEDURE

Completion of the tasks involved:

1. Desktop review of existing information
2. Geomorphic mapping based on available aerial photography, satellite imagery and landscape photography followed by field verification at selected sites
3. Execution of a ground-based field survey of the beach and foredunes, and an aerial survey of the dune lands both along the open ocean coast and the western shore of Lake Preston.
4. Data analysis and compilation of photographic records
5. Reporting the results of the desktop studies and field surveys, including presentation of recommendations concerning any requirements for further studies and potential use of the lands from a risk management perspective.

1.2.1. Geomorphic Mapping

Geomorphologic attributes interpreted from available aerial photography and satellite imagery included:

1. Description of the presence, absence and offshore distance of rocky features in the nearshore and along the beach;
2. Extension of available records of shoreline movement compiled by the Department of Transport through overlay on recent aerial photography; and
3. Identification and description of dune topography, particularly the foredunes and frontal dunes.

1.2.2. Fieldwork

Aerial reconnaissance by helicopter was completed on 6 February 2009. The survey enabled comprehensive high angle oblique photography of the beaches and dunes as well as landing for ground inspection and description of the geomorphology at regular intervals along the beach. Additionally, ground surveys of the beaches and dunes were completed at points along the coast accessible by 4WD vehicle.

All photographic records are included as a DVD in Attachment 1. The information has been separately incorporated in a more extensive survey of coastal geology and geomorphology being undertaken by the Geological Survey of Western Australia.

2. REGIONAL CONTEXT

The Yalgorup Coastal Plain has been defined by Semeniuk (1995) as a single geomorphologic entity approximately extending northwards from Bunbury. The coastal Holocene Barrier Dunes and the Mandurah-Eaton Ridge, which respectively form the western and eastern boundaries of the Yalgorup Plain, meet at south Dawesville (Figure 1). As described by Semeniuk (1995: 68) the Plain is 60 km long, 5 to 6 km wide, generally less than 15 m in elevation and formed on a limestone platform of Pleistocene age. It is bordered to the west by an aeolian dune ridge of Holocene age, the Leschenault-Preston barrier, which is underlain by a Pleistocene platform. The dune ridge and the shore adjacent to it are the subject of this report and, for convenience, are referred to herein as the Yalgorup Coast. Along the Yalgorup Coast the Leschenault-Preston Barrier is narrow. It ranges in width from approximately 0.8 to 2.0 km seaward from the western shore of Lake Preston. Active, mobile dunes extend from the ocean shore up to 1.0 km inland over older, vegetated dunes up to 40m in elevation. The barrier is lowest in the south between Binningup and Myelup where dune heights are generally less than 20m. North of Preston Beach the dunes rise up to 40m in places but are commonly between 20m to 30m elevation.

The geology of the southwest region is divided by the Darling Scarp between the Yilgarn Block to the east (Precambrian granites) and the Perth Basin to the west, with mostly Cretaceous limestone (Gozzard 2007). Quaternary limestone formations are expressed along parts of the coast, and in nearby islands and reef chains. Below the Darling Scarp, the surface sediments of the Swan Coastal Plain are comprised of a sequence of weathered coastal dune systems, including sands comprising the Bassendean, Spearwood and Quindalup soils listed in order of decreasing age and generally westerly expression. The sequence has resulted from sea level fluctuations in the Late Quaternary (McArthur & Bettenay 1974; Semeniuk 2000).

The Yalgorup Coast is dominated by the Quindalup Dunes, an extensive sequence of coastal dune ridges, comprised of Safety Bay Sands (Figure 2), which have been reworked over the Holocene period, approximately the last 6,000 years (Cresswell 2000). The nature of this sedimentary unit is described by Woods (1983), who notes high along-coast variation in carbonate contents from 35% to 90% by weight. The dunes have extensive aeolian characteristics, including multiple dune face blowouts and sand sheets (Byrne *et al.* 1985).

Semeniuk *et al.* (2000), describe the evolutionary sequence of the Yalgorup coastline (Figure 3). Unlike the majority of southwest Australia, the shore is not markedly defined by outcropping of Pleistocene limestones but is almost solely derived from Holocene reworking of mobile sediments. Further evidence regarding the mobile nature of the sediments in the wider region was provided through the use of boreholes, cone penetrometer and micro-tremor seismic data (Jones 2005). The few boreholes taken through the frontal dune ridge showed no rock above -10m AHD, although isolated sampling slightly further east identified some rock between 0 and –10m AHD. However, this is not supported by the field and photographic records developed within the present study or the more extensive investigations undertaken by Geological Survey of Western Australia (Gozzard 2007).

Rocks outcrop as the South Bank Ridge form a pavement platform on the Inner Shelf Plain between the Leeuwin Naturaliste Ridge and the Bouvard Reef Ridge. However, the Yalgorup Coast is not protected by the extensive limestone ridges that form offshore reefs along much of the central and south west coast of Western Australia. Although emergent rock outcropping is sparse and irregular, some rock features are apparent offshore as well as being present near shore but submerged. The coastal morphology is dominated by a sequence of large coastal dunes, up to 60 m elevation above sea level and of Holocene age (Figure 3). Much of the foreshore is sharply scarped, with extensive blowouts present along the foredune ridge.

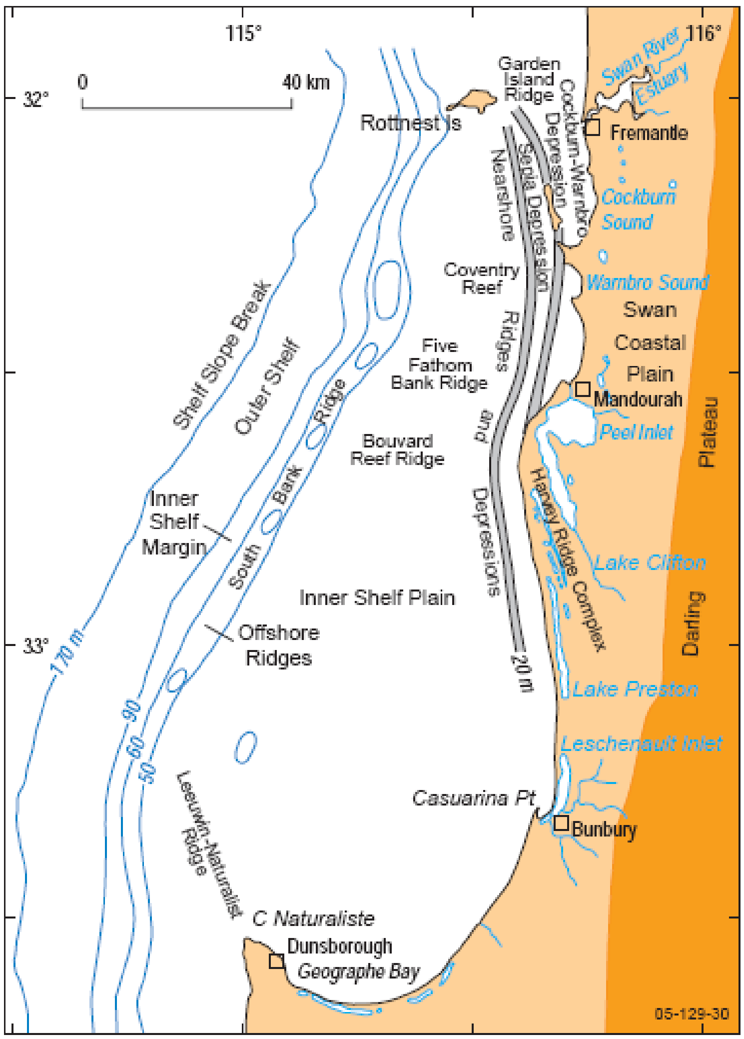


Figure 1 Morphology of Naturaliste to Rottnest Shelf

The coast from Cape Naturaliste to Cape Bouvard, south of Mandurah, and along the Garden Island Ridge to Rottnest Island constitutes a single compartment. Smaller sediment cells are defined by transitions at Casuarina Point, Cape Bouvard, Roberts Point and Becher Point. (Map from Richardson *et al.* 2005)

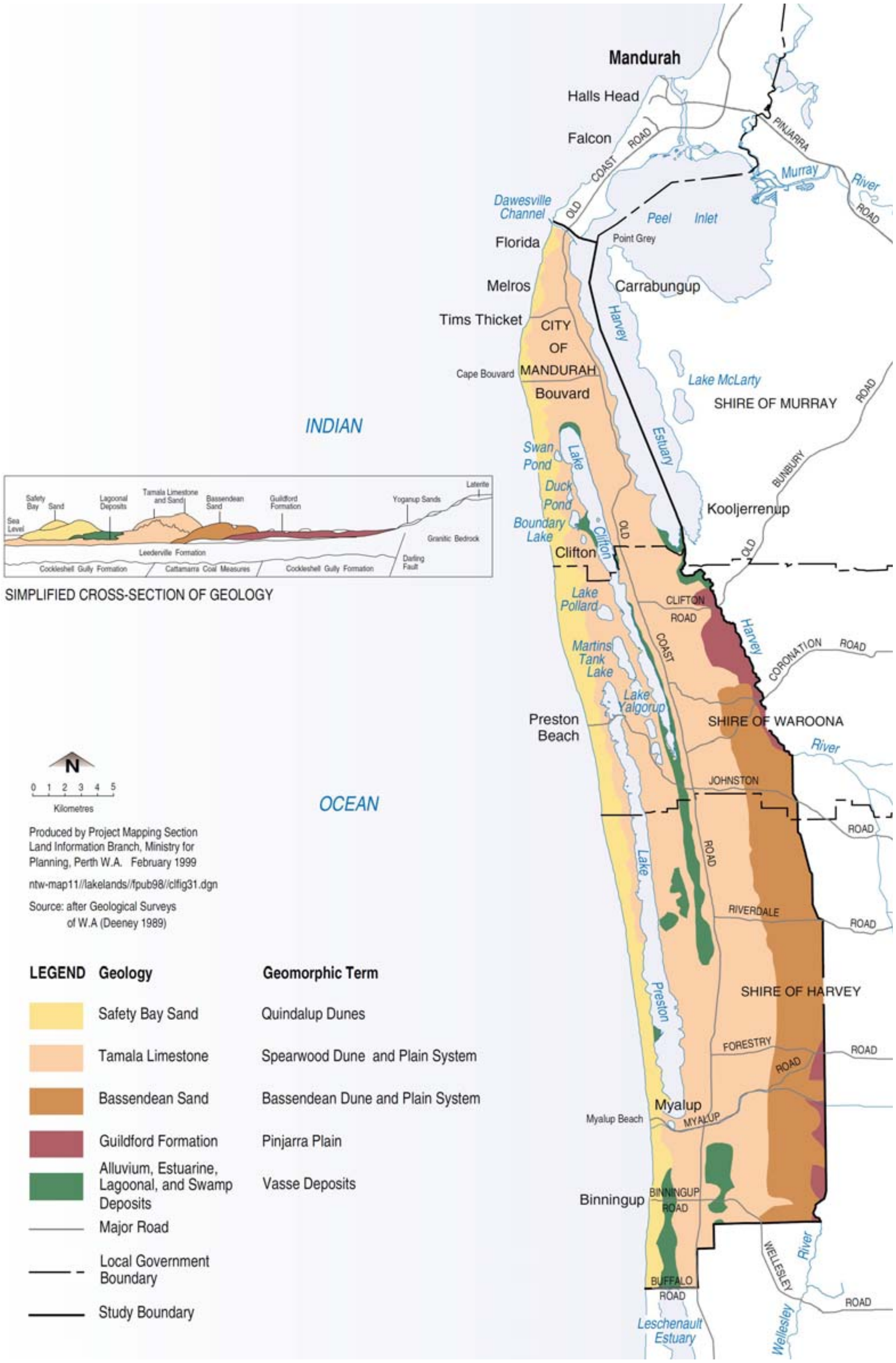


Figure 2 Simplified Geology

From WAPC 1999 Coastal and Lakelands Planning Strategy

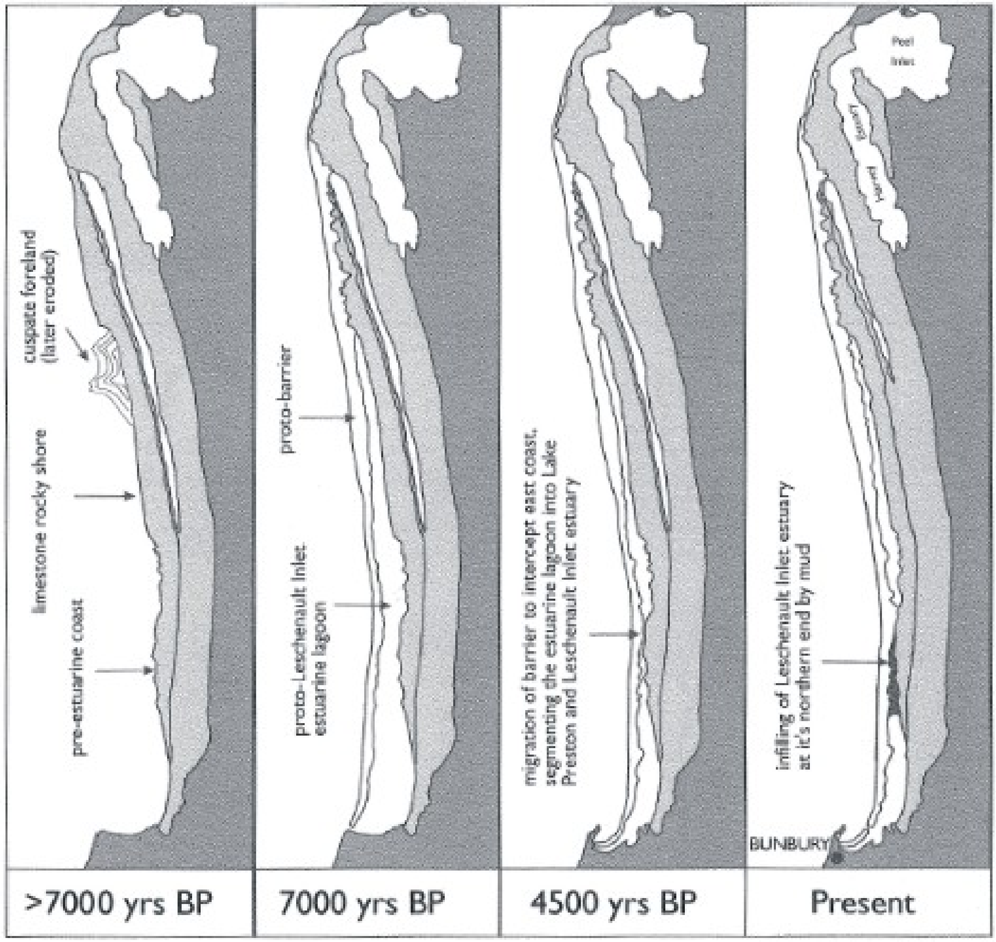


Figure 3 Coastal Evolutionary Sequence

Extract from Semeniuk *et al.* (2000)

2.1. COASTAL CHANGE

Coastal change occurs over a wide range of temporal and spatial scales. A conceptual framework under which observed change can be assessed 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). More slowly varying processes provide extrinsic forcing, whereas more rapidly varying processes cause fluctuations that have a reduced residual effect when considered over an extended period. This framework is often used to justify four distinct 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 Plaasche 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 moderate (geomorphic) scales, coastal evolution is determined by the production of mobile sediments, transfer via metocean forcing, and accumulation in zones of relative shelter. This suggests simulation of coastal change using sediment sources or sinks, and prompts the concept of equilibrium coastal alignment;
3. Over short (planning) scales, large scale sinks and sources of material may be considered constant and the 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.

2.2. THE GEOLOGICAL FRAMEWORK

The Yalgorup Coast is an onshore component of a large coastal sediment compartment extending from Cape Naturaliste to Rottnest Island. Coastal compartments are distinguished from sediment cells in this report. Coastal compartments primarily relate to structural control by the regional geology. They are secondarily dependent on coastal aspect and large coastal landforms such as tombolos and cuspate forelands. In contrast to the compartments, sediment cells are smaller functional units defined by the movement of unconsolidated sediments within geomorphic and geologic boundaries. To a lesser degree the distinction is based on the potential ease of determining a sediment budget from available information. Each of these concepts – compartments, cells and budgets – warrants description although all have been described elsewhere. For examples, see descriptions in texts by Komar (1996) and Short (1999).

Coastal sediment compartments are large, regional scale features of the coast. They are comprised of a complex array of physical landforms and coastal processes in which the state of the environment is dynamic, varying over space and time. The array of landforms differs between adjacent compartments with respect to characteristic landforms, coastal processes or some combination thereof. Each compartment extends from the landward reach of tidal waters to the effective offshore limit of sediment movement, and thus includes the terrestrial coastal zone, intertidal shore, inshore and inner continental shelf waters.

A coastal sediment compartment is a natural management unit with regard to the conservation of sediment and ecosystems as well as mitigation of environmental risks. Potentially, managing the coastline through an approach based on sediment compartments provides focus on management of change through recognition of what is changing and potentially provides scope for proactive adaptation to changing circumstances. This is one element of rationale for suggesting coastal management and marine conservation plans should be founded on coastal compartment concepts.

While the exact boundaries of the compartment have yet to be determined the topography of the inner continental shelf indicates it is bounded offshore by the Leeuwin Naturaliste Ridge to the south and the semi-continuous South Bank Ridge to the west (Figure 1). The shoreface is a distinct sub-component of the compartment, being the near coast zone in which sediment is most commonly moved by waves. For the Yalgorup coast, the shoreface may simplistically be defined as shoreward of the 20 m isobath. From Binningup northwards to Rottnest Island, the shoreface includes a series of ridges and depressions that provide natural structures for northwards sediment movement with a potential feed of sediment offshore onto the Five Fathom Bank or into the Sepia Depression north of Cape Bouvard. The Leeuwin Naturaliste Ridge and the South Bank Ridge provide the geologic framework upon which large scale geologic and geomorphologic processes are evident. The framework is expressed through the Quaternary formation of the limestone topography, and Holocene evolution of the coastal sand barrier, in response to sea level fluctuations.

At a more local scale the nearshore ridges and depressions of the shoreface limestone extend under the modern beach and dunes and 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 since 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).

Cleary et al. (1996: 250) stressed the role the inherited geologic framework plays in determining barrier morphology, coastal cell evolution, and shoreface dynamics. 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 the Yalgorup Coast since the Holocene coastal barrier overlies, or is perched on, an irregular limestone platform of older Quaternary origin. Superficially, five coastal sediment cells are discernable as shallow embayments between salients along the shore with each salient landward of a nearshore rock outcrop (Figure 4).

A sediment cell is a reach of coast, including the nearshore terrestrial and marine environments, within which movement of sediment is largely self-contained. Some sediment exchange across boundaries between adjacent cells may occur, although this is generally limited and highly variable over time. Boundaries can be fixed, due to the presence of rocky headlands or structures, or migratory with changing wave conditions (Carter 1988). When sediment exchange is limited, a sediment cell may be used for estimation of a coastal sediment budget (Komar 1996; Rosati 2005) and identification of areas undergoing erosion or accretion and the linkages between them. Although interruption at a cell boundary arguably should not significantly affect adjacent cells (Mc Innes *et al.* 1998) this is not the case along the Yalgorup Coast where alongshore transport is pronounced, and sediment exchange between cells is high.

Whether morphologic changes within the cells reflect spatial variation in the coastal energy regime is highly probable but open to question. Here, the cells have been used to structure identification of the geomorphology of the coast and nearshore waters as well as for comparative purposes establish areas of relative instability along the coast between Binningup and Cape Bouvard.

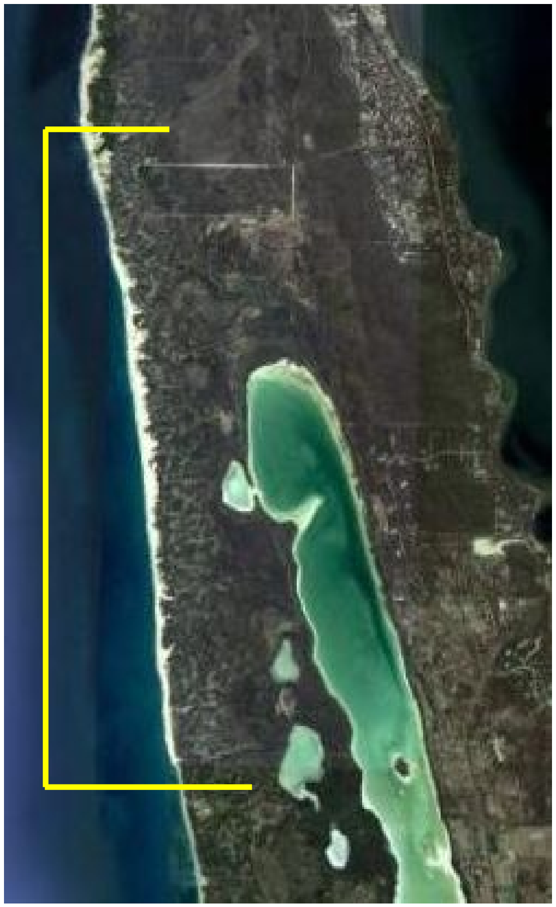
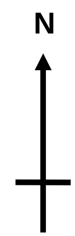
Cell 1 – White Hills Road	Cell 2 – Lake Clifton North	Cell 3 – Preston Beach
		

Figure 4 Sediment cells along the Yalgorup Coast

Cell 4 – Lake Preston South	Cell 5 – Myalup
	



Note: Images are indicative and not to scale

(Source: Google Earth 2009)

Figure 4 (Continued) Sediment cells along the Yalgorup Coast

3. COASTAL PROCESSES

Coastal stability may be 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. For this project, a hierarchy of geomorphic features, based upon spatial and temporal variability (Figure 5), has been used to help identify active processes likely to determine the stability of the Yalgorup Coast.

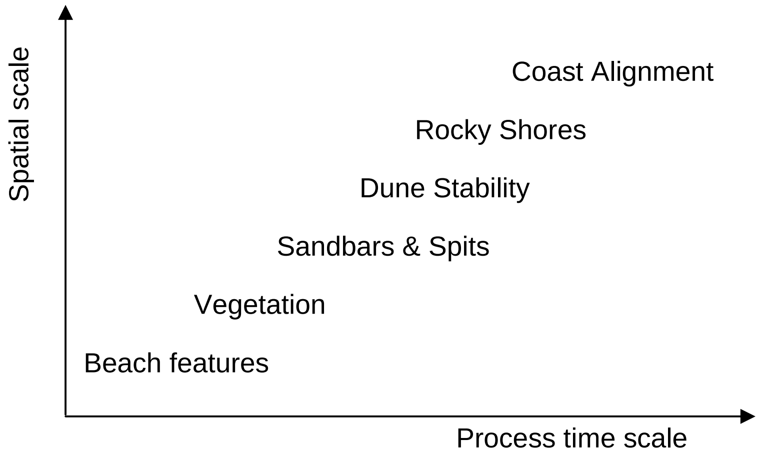


Figure 5 Hierarchy of Coastal Features

Coastal processes reviewed include meteorological conditions contributing to the wind, wave and nearshore current regime, as apparent in records from the nearest meteorological station, at Bunbury. Particular reference is made to extreme weather events likely to generate storm surge or significant aeolian transport of sediment for dune formation. Tides and surges are described for water level records from Bunbury, while descriptions of wave conditions have been obtained from Bunbury, Dawesville and Rottnest waverider buoy and acoustic wave recorder deployments. The specific information used has been detailed in each section.

3.1. METEOROLOGY

South-west Western Australia experiences a relatively mild climate, with cool wet winters and hot, dry summers, commonly described as Mediterranean (Figure 6). The region lies within the southern half of the extra-tropical ridge and is dominated in summer by eastward travelling high pressure systems, within 26^{o}S to 45^{o}S, which cross the coast every 3 to 10 days (Gentilli 1972). During winter, a northward movement of the pressure belts allows the impact of mid-latitude low-pressure systems from latitudes 35^{o}S to 50^{o}S to increase, through fronts or more direct synoptic winds from northerly travelling systems. The influence of tropical systems is rare, although it may be significant, as amply illustrated by the impact of TC Alby in April 1978.

Climate summaries from the Bureau of Meteorology for Bunbury AWS, to the immediate south of the Yalgorup Coast, from 1995 to 2007 describe the seasonal ambient variations.

The land-sea breeze cycle dominates the prevailing winds of the region, particularly over summer, with moderate easterly winds in the morning and stronger (up to 15 m/s) southerly sea breezes in the afternoon commencing around noon and weakening during the night (Pattiaratchi *et al.* 1997). Unlike the ‘classic’ sea breeze, these sea breezes blow parallel to the coastline; their onset is rapid, initial velocities are relatively high, and the surface currents respond almost instantaneously (Pattiaratchi *et al*. 1997). The sea breeze may occur in all seasons, although it is most frequent and intense during summer months (Masselink & Pattiaratchi 1998).

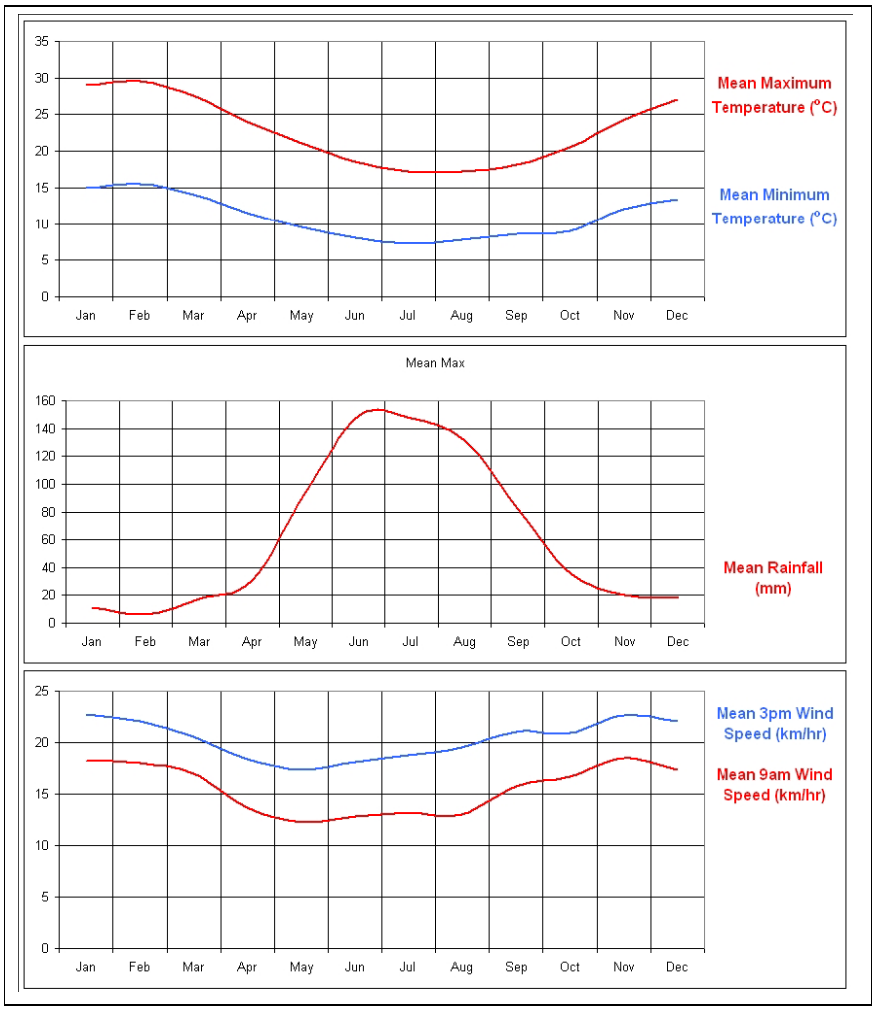


Figure 6 Mean Monthly Temperature, Rainfall & Wind Speed
Data from Bureau of Meteorology (2007)

3.1.1. Weather System Characteristics

The average wind speed, direction, duration, extremes and event frequency for the main weather systems experienced on the Perth Metropolitan Coast have been summarised by Stul (2007) and are listed in Table 1. It is expected that these will be similar for the Yalgorup Coast, although with marginal deviations in strength and direction of winds.

Table 1 Main Local Weather Systems

Weather System	Anticyclones	Squalls	Mid-latitude Depressions	Dissipating Tropical Cyclones	Sea Breezes
Occurrence	Annual	Dec – Apr	May – Oct	Oct – Mar	Oct – Mar (mainly)
Avg Wind Speed	Light	15-20 m/s	15-29 m/s	15-25 m/s	10 m/s
Avg Duration	Unknown	2-4 hours	10-55 hours	5-15 hours	~7 hours
Avg Wind Direction	All	All	N to NW to W to SW	Depends on path	180-200^o
Extreme 30 min avg					
Frequency	3-10 days	13 days	3-8 / year	1 in 10 years	> 15 days/month
References	Gentilli 1972	Steedman 1982	Gentilli 1972; Steedman 1982	Gentilli 1972; Steedman 1982	Pattiaratchi *et al*. 1997

3.1.2. Storm Events

High wave conditions on the southwest are almost exclusively related to onshore wind conditions from the northwest through southwest (Lemm 1996). Studies of storm event climatology and extreme wind analysis (Steedman & Craig 1983; Steedman & Associates 1982) have identified that sustained high winds in the southwest region occur from five sources:

1. Dissipating Tropical Cyclones
2. Sea Breezes
3. Extra-tropical Cyclones
4. Pre-frontal Troughs
5. Cold Fronts

The last three sources of sustained high winds above are all caused by mid-latitude depressions, although the mechanism and extent of wind generation may be considerably different. Approximately 20 storms per year were identified, most frequent during July. During the passage of a frontal system, the region is subject to strong winds (up to 25–30 m/s) from the north-west, which rapidly change direction to the west then south-west over 12–16 hours. The south-westerly winds gradually weaken over two to three days, and calm, cloud-free conditions may prevail for another three to five days before the passage of another frontal system.

Analysis of the synoptic records indicated that mid-latitude storms may cause strong winds from all westerly directions – NNW through to SSW (Panizza 1983). During the period 1968-1982, strong northwesterly storms were identified in 1968, 1973-1975, 1977 and 1980-1981. Strong southwesterly storms were more evenly distributed, with severe events in 1970-1973, 1975, 1977-1978 and 1981.

The most well-known storm events are the most unusual, or those in recent memory. These include storms in April 1978 (TC Alby), June 1996 and May 2003.

3.2. COASTAL CLIMATE

The Yalgorup Coast is located approximately between latitudes 32^{o} 41'S and 33^{o} 09' S on the west-facing coast of Australia. It is exposed to wave generation from the Southern and Indian Oceans, experiencing a variable, sometimes high-energy coast as measured offshore from Garden Island and Rottnest (Riedel & Trajer 1978; Lemm 1996; Department of Transport 2009). Wave generation occurs principally over the extended fetch of the southern Indian Ocean, providing a background swell that is comparatively slowly varying, which combines with highly variable locally generated wind waves (Lemm 1996). Prevailing swell is south to southwest, generated from mid-latitude synoptic systems, with enhanced west to northwest activity during winter months.

Elevated wave conditions are associated with a range of synoptic events, which may vary in latitude, intensity, frequency and mobility (Karelsky 1961; Steedman & Craig 1983; Trenberth 1991). The aspect common to these events is the occurrence of onshore winds, although direction may vary from southwest to northwest (Panizza 1983). Applying this characteristic, a measure of storminess has previously been established for the period 1962-1980 using winds from Fremantle (Steedman & Associates 1982).

3.2.1. Wind Conditions

The closest and longest set of observations to the Yalgorup Coast is the Bunbury wind record, observed since the 1890s. However, instrumented measurement of wind data for Bunbury did not occur until 1965 through the Bureau of Meteorology. The location of the weather station used for sampling has subsequently been changed on two occasions. Although this apparently affected median wind speeds, the range of directions observed and the speed of strong winds were consistent between sites (Table 2, Figure 7 and Figure 8). Maximum observed wind speeds are significantly different between data sets, but this is typical for extreme conditions. Dominant wind directions are east-southeast and southwest-northwest. It is unclear whether the local coastal topography at Bunbury influences these measured directions, as they contain significantly fewer southerly winds than Garden Island or Rottnest observations, which are two of the longest coastal wind records held by the Bureau of Meteorology.

Table 2 Bunbury Wind Observations

Station	Location	Dates	50% Wind	90% Wind	Max Obs
9514	Bunbury Post Office	1965 – 1985	9 km/hr	28 km/hr	96 km/hr
9885	Bunbury Power Station	1985 – 1995	13 km/hr	28 km/hr	148 km/hr
9965	Bunbury AWS	1995 – 2008	15 km/hr	26 km/hr	65 km/hr

Using wind speed and direction data obtained from the Bureau of Meteorology from the period January 1985 to September 2004, a simple extreme event analysis has been undertaken for Bunbury. It should be noted that much of the wind data has been derived from Beaufort wind scales, which have been converted to equivalent wind bands. This creates an artificial stepping of the extreme wind speeds and affects the statistical reliability of the fit (Figure 8). Furthermore, the relatively short sampling period dictates that the analysis is only relevant for events less than 100 years average recurrence interval (ARI).

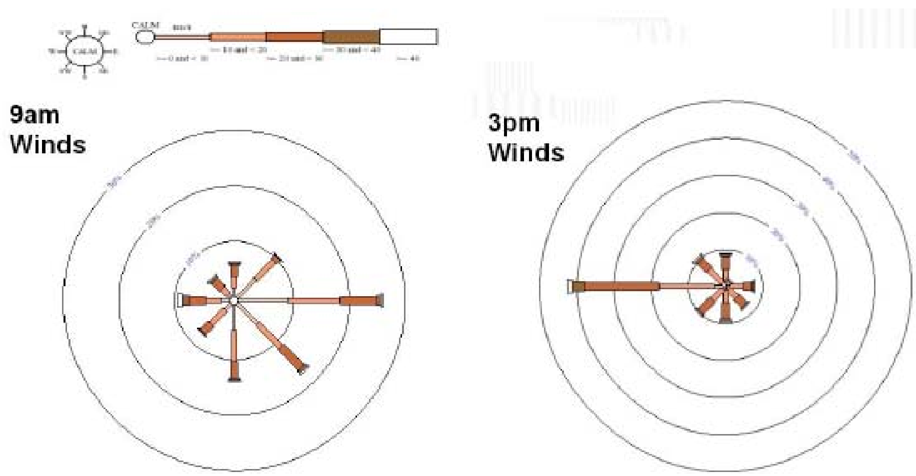


Figure 7 Average 9am and 3pm Winds (1995-2006)
Extracted from Bureau of Meteorology (2007)

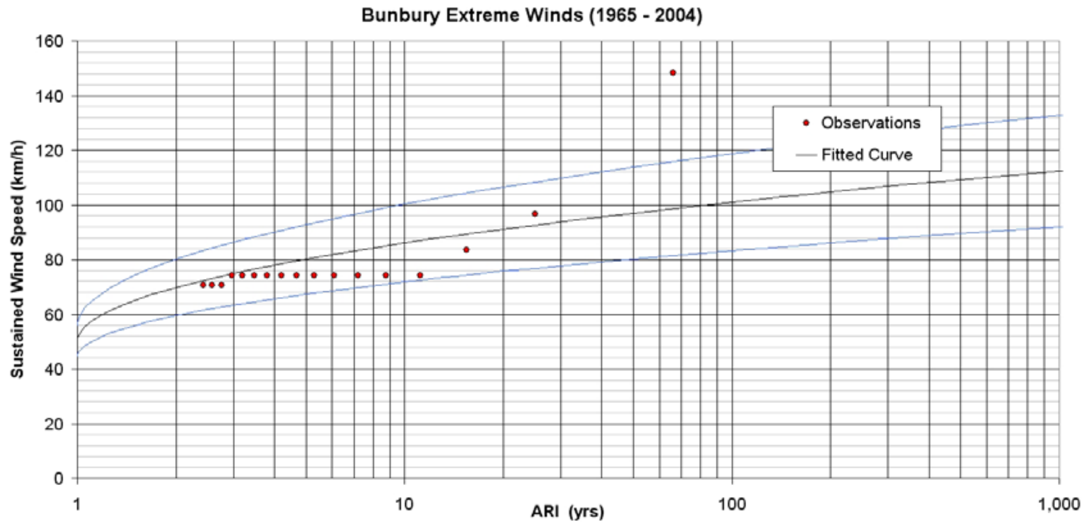


Figure 8 Extreme Wind Analysis for Bunbury
(From Damara 2008)

3.3. WATER LEVELS

The nearest location of sustained water level observations to the Yalgorup Coast is from Bunbury, where recordings have been made since 1930, originally using a Bailey drum tide gauge (Hamon 1963). However, the reliability of early sea level records has been questioned, and it is considered unlikely the reference datum was stable prior to additional survey control instigated during the Australian mean sea level survey to establish Australian Height Datum from 1965 (Easton 1970; Wallace 1988). Furthermore, the original gauge was largely constrained to measure from –0.3 to +1.8m relative to the gauge datum (Hamon 1963). Higher levels have been recorded since the gauge type was upgraded in 1966. The annual maximum water levels from 1930 to 2008 are illustrated in Figure 9 and the water level record from 1998 to 2008 shown in Figure 10.

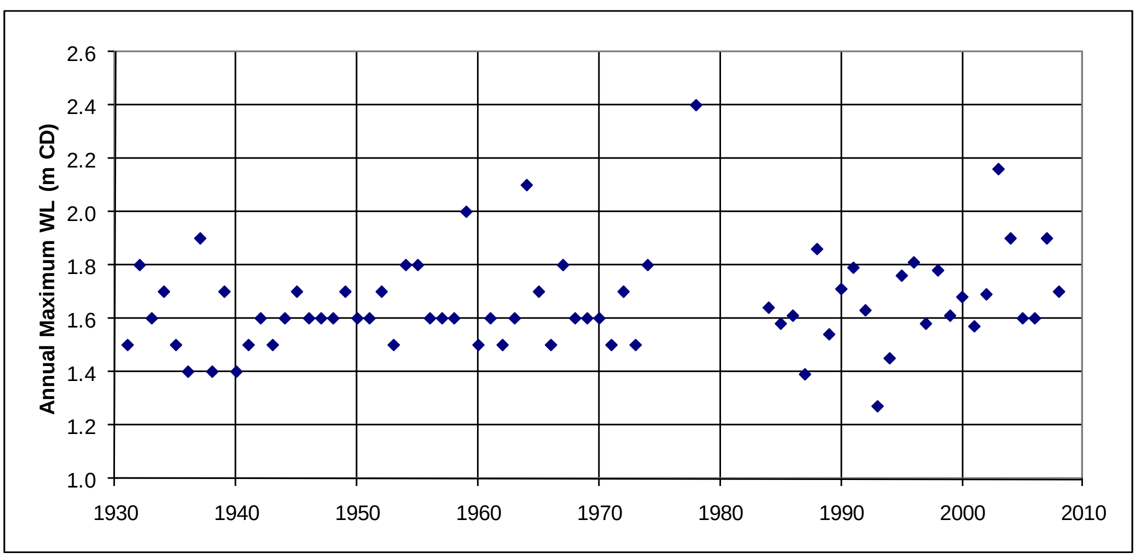


Figure 9 Annual maximum water levels 1930 to 2008

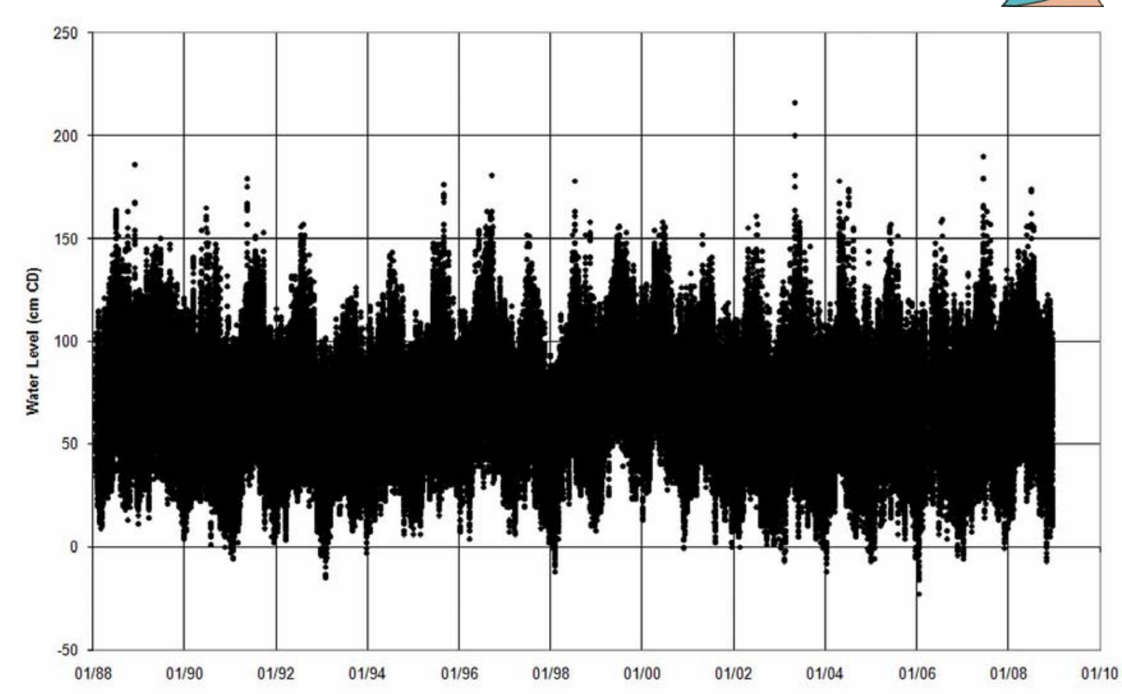


Figure 10 Bunbury water levels 1998 to 2008

Several analyses of the Bunbury water level record have been undertaken, principally to define requirements for the flood protection system protecting Bunbury central business district, particularly subsequent to flooding that occurred during TC Alby (Bower 1976; PWD 1980; CMPS&F Pty Ltd 1997; McGrath 1998). Much of this analysis has recently been revised to incorporate recent data following observation of an increased number of high water level events (DPI unpublished analysis).

A simple summary of the water level record is suggested by the submergence curve for Bunbury, showing the tidal planes and extreme observed water levels (Figure 11). It should be noted that this curve is schematised and does not actually represent the cumulative distribution of observed water levels.

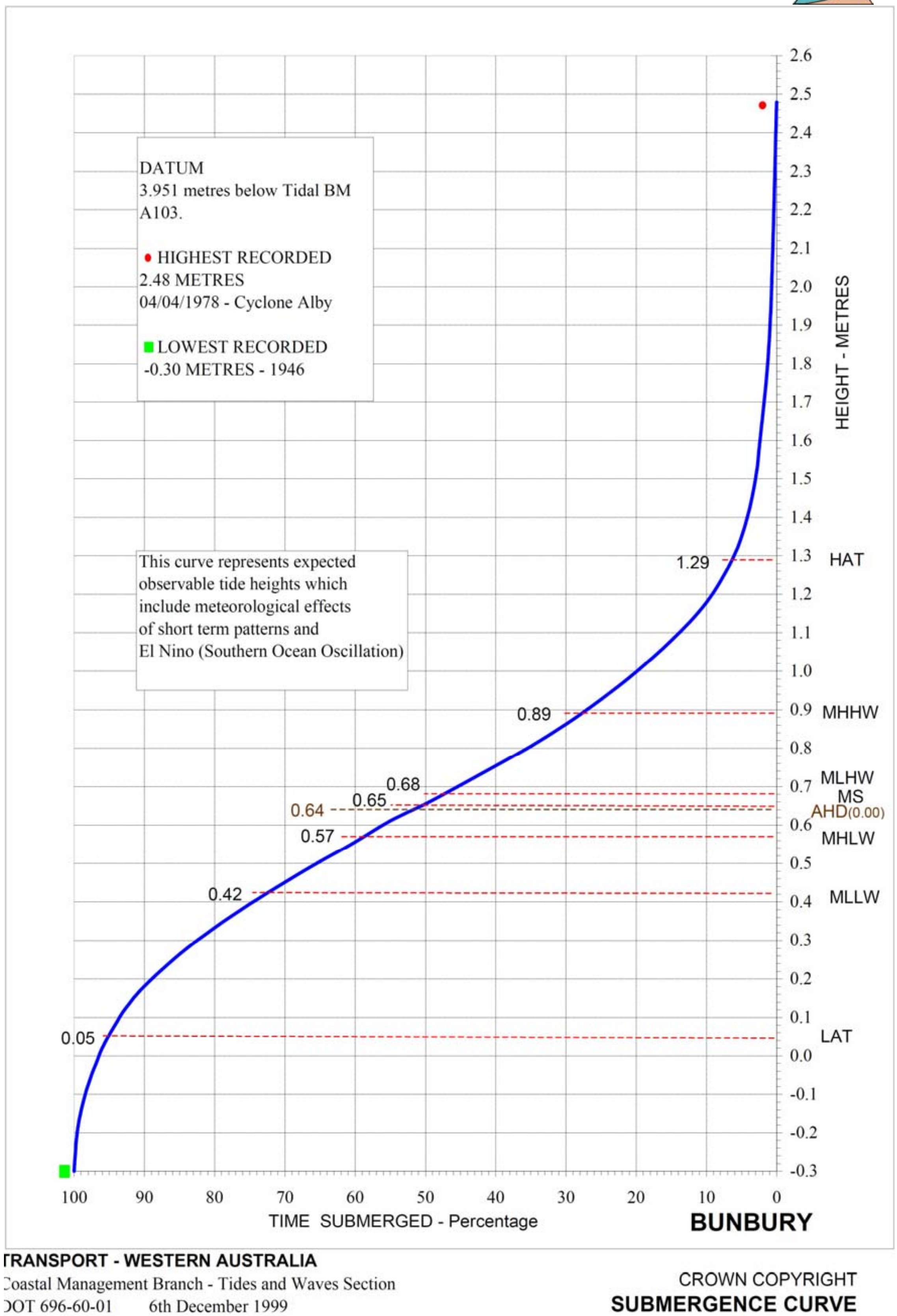


Figure 11 Bunbury Submergence Curve

3.3.1. Tides

Bunbury is one of the Standard Ports defined by the Royal Australian Navy Hydrographic Office, with annual tidal predictions published in the Australian National Tide Tables. Bunbury experiences a principally diurnal tide, with a microtidal range of 1.4m from LAT to HAT (Table 3), of which approximately 0.3 m is produced by the seasonal mean sea level cycle (Pariwono *et al*. 1986).

Table 3 Bunbury Tidal Planes

Tidal Level		Water Level (m CD)
Highest Astronomical Tide	HAT	1.3
Mean Higher High Water	MHHW	0.8
Mean Lower High Water	MLHW	0.5
Mean Sea Level	MSL	0.6
Mean Higher Low Water	MHLW	0.6
Mean Lower Low Water	MLLW	0.3
Lowest Astronomical Tide	LAT	-0.1

The tidal sequence is strongly affected by monthly, seasonal and inter-annual signals (Figure 12). It should be noted that the seasonal signal, which ranges approximately 0.3m and peaks in June, is believed to be the result of steric and wind stress variation rather than an astronomic tide. The tidal range varies on a bi-annual cycle, with peaks at the summer and winter solstice. It is further modulated by the 19-year lunar nodical cycle, which is exaggerated in Figure 12 by the effect of relocating the tide gauge. Analysis of the long-term Fremantle data set suggests peaks in 1987 and 2006.

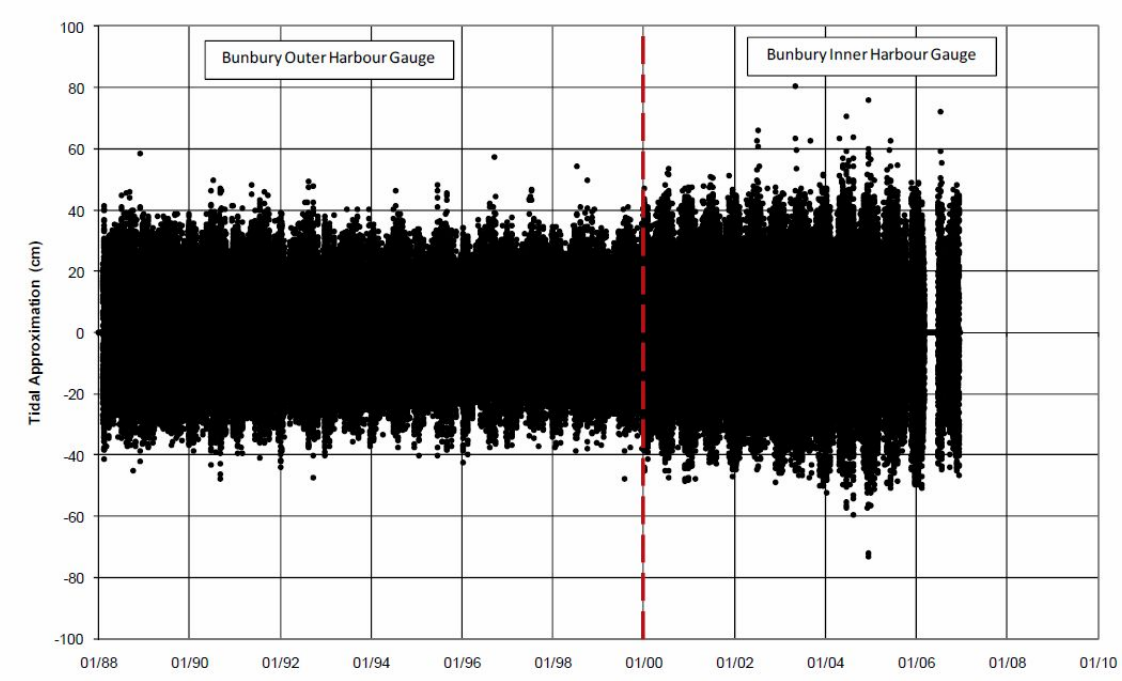


Figure 12 Tidal Approximation for Bunbury 1988 to 2006

3.3.2. Surges

The contribution of surges to the water level record in the Bunbury region is high (Figure 13), and their relative importance is amplified by the small tidal signal. The relative significance of non-tidal water level phenomena is expressed within the Australian National Tide Tables with the footnote:

> *At Fremantle the water level is erratic, being almost entirely governed by the weather. During and after westerly gales, a high level of up to about 1.2m is maintained for several days (possibly up to 6). In easterly weather, a very low level may be experienced for a similar period of time. (Department of Defence 2006)*

This dependence upon weather conditions was also noted by Provis & Radok (1979), and suggests that the majority of surge is atmospheric in origin, related to mid-latitude storms. Additionally, surges may occur due to more unusual meteorological events such as Tropical Cyclone Alby (Figure 14) or through remotely generated shelf waves, which can positively interact with atmospheric surge (Figure 15). High surge conditions may induce substantial albeit commonly short lived beach responses.

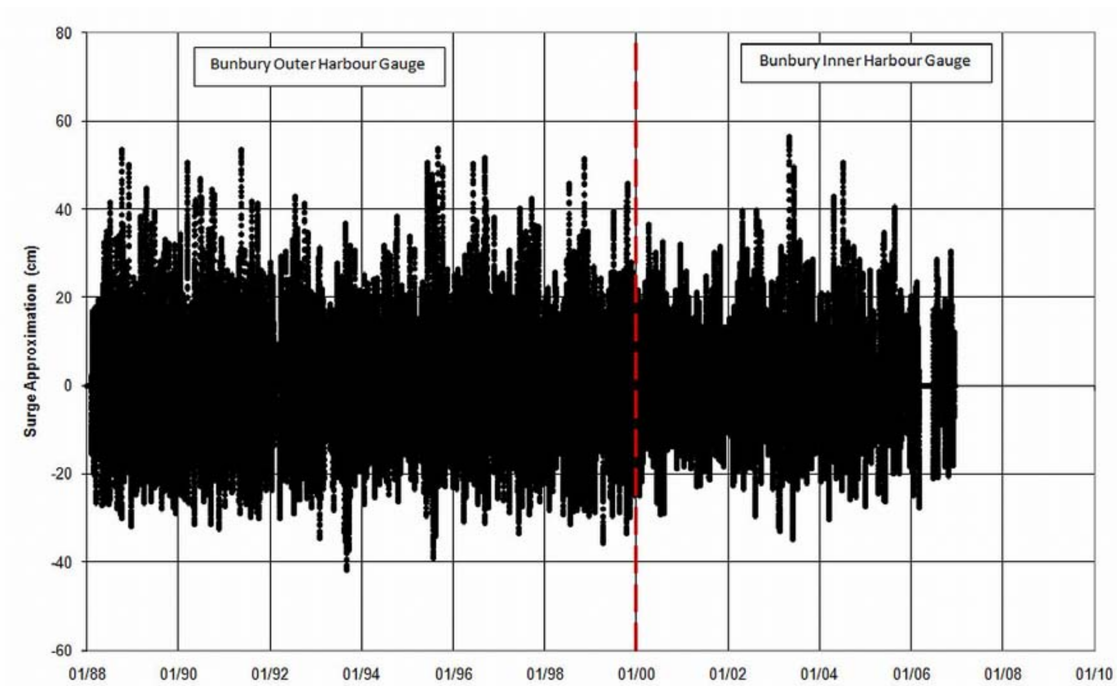


Figure 13 Surge approximation for Bunbury 1988 to 2006

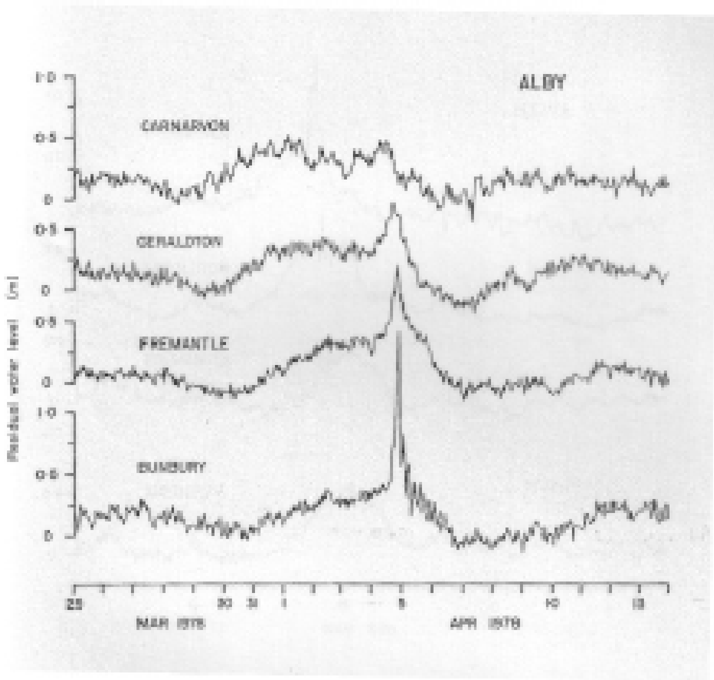


Figure 14 Tidal Residual Observations for TC Alby
Extracted from Fandry *et al.* (1984)

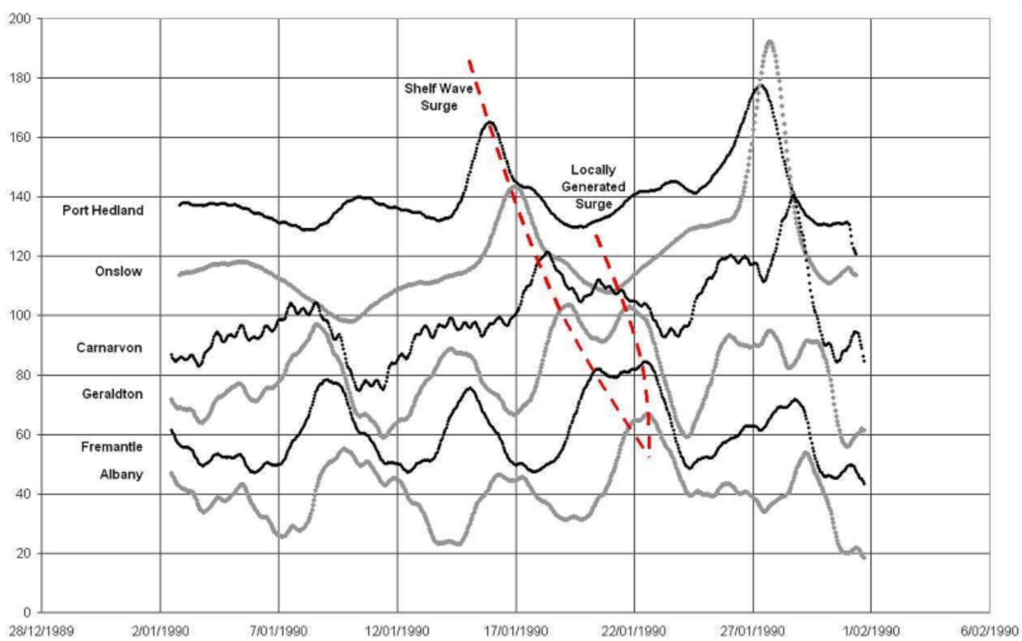


Figure 15 Shelf Wave Interaction with Locally Generated Surge

3.3.3. Mean Sea Level Variations

The 30-day running mean of water levels indicates two significant sources of slowly varying sea level fluctuations, at seasonal and inter-annual time scales (Figure 16). Comparison of the long-term record for Bunbury (1957-2004) suggests a mean sea level rise of 1.2 mm/year, although there is some doubt regarding the validity of the data before 1966 (Damara WA 2008). The trend for any time period is strongly affected by inter-annual fluctuations, and therefore should be interpreted with caution.

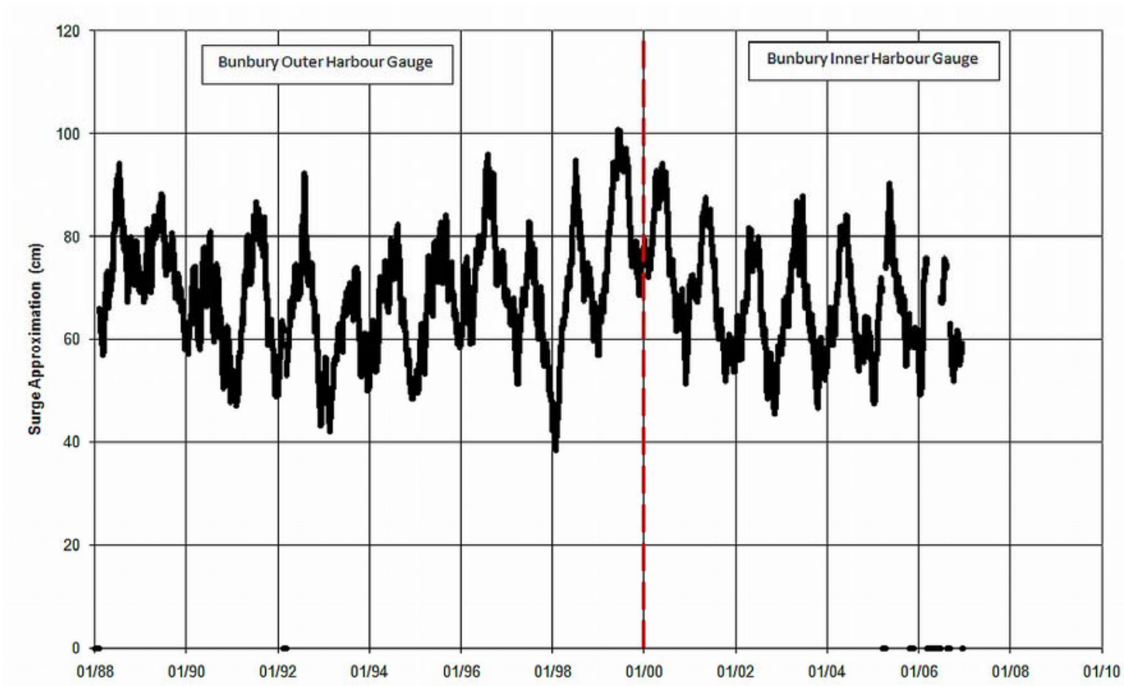


Figure 16 Bunbury 30-day Running Mean Sea Level (1988-2006)

The inter-annual relationship between mean sea level and climate fluctuations is suggested by a strong correspondence between annual average water level and SOI - the Southern Oscillation Index (Pattiaratchi & Buchan 1991). 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 17 occurs along the entire Western Australian coast (Pariwono *et al.* 1986).

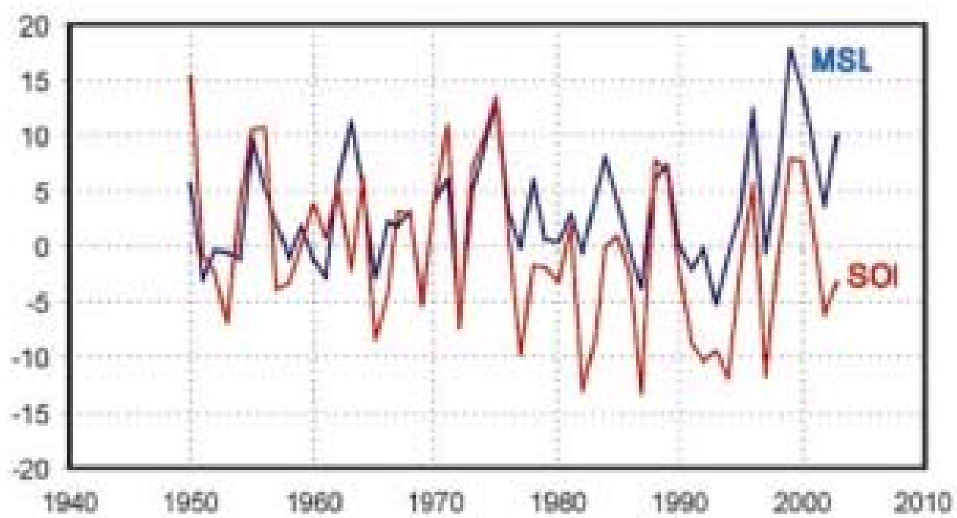


Figure 17 Correspondence Between Fremantle Mean Sea Level and SOI

3.3.4. Extreme Water Levels

The 1980 study of Bunbury Ocean water levels for the storm surge barrier included an analysis of the largest storm surges between 1974 and 1978, with an extreme water level analysis from 1930 to 1978 (PWD 1980). Using more recent data from Bunbury over the period 1987 to 2004, a “recent climate” extreme distribution has been derived (Damara WA 2008). This illustrates the relative instability of such analyses for extreme events, where the occurrence of three high events in the period 1930-1978 causes higher extreme event estimates for ARI 20 years or above (Table 4).

Table 4 Bunbury Extreme Water Levels

Approximate Return Interval	Water Level (m CD) 1930-1978	Water Level (m CD) 1987-2004
2 years	RL 1.63 m CD	RL 1.70 m CD
5 years	RL 1.75 m CD	RL 1.80 m CD
10 years	RL 1.84 m CD	RL 1.86 m CD
20 years	RL 1.97 m CD	RL 1.91 m CD
50 years	RL 2.20 m CD	RL 1.98 m CD
100 years	RL 2.38 m CD	RL 2.00 m CD

3.4. WAVES

Wave measurements around southwest Australia have been historically collected by Federal and State government agencies, including observations at the major ports and other locations where major coastal facilities are planned. From 1971 to 1994, these measurements were sporadic in nature, typically through comparatively short term deployments of one to four years. Deployments included measurements at Garden Island, Fremantle, Bunbury and Dawesville Channel (Reidel & Trajer 1978; Buchan *et al*. 1987).

From 1993, a series of permanent offshore waverider buoy deployments have been progressively undertaken to provide a regional description for the wave climate throughout the southwest. The two buoys most relevant to the Binningup-Myalup region are those at Rottnest and Cape Naturaliste. The Rottnest buoy was upgraded to a directional buoy in 2002.

Comparison of the wave climate between locations does not suggest a systematic spatial variation, with quite variable conditions between sites. However, modelling of the wave climate for the southwest region has suggested comparatively little spatial variation over the Bunbury to Rottnest offshore region (Steedman & Associates 2001; Richardson *et al.* 2005). Hence the discrepancy of wave climate descriptions between sites may partially be explained by the different occasions over which the waves were observed, noting that a high level of inter-annual variability has been identified at sites with more than one or two years of record. Consequently, it is suggested that an extended period of record needs to be used when interpreting wave conditions.

3.4.1. Garden Island Waverider Deployment

The first extended deployment of an offshore wave measuring instrument was undertaken by the Commonwealth Department of Construction from 1970-1975 as part of investigations for the development of Stirling Naval Base at Garden Island (Reidel & Trajer 1978). Analysis of the wave observations estimated a 1-year ARI significant wave height of 4.4m and a 10-year ARI height of 6.1m, in a depth of 40m. However, high variability on a year-to-year basis occurred, suggesting a low certainty in the estimation of extreme wave parameters (Figure 18).

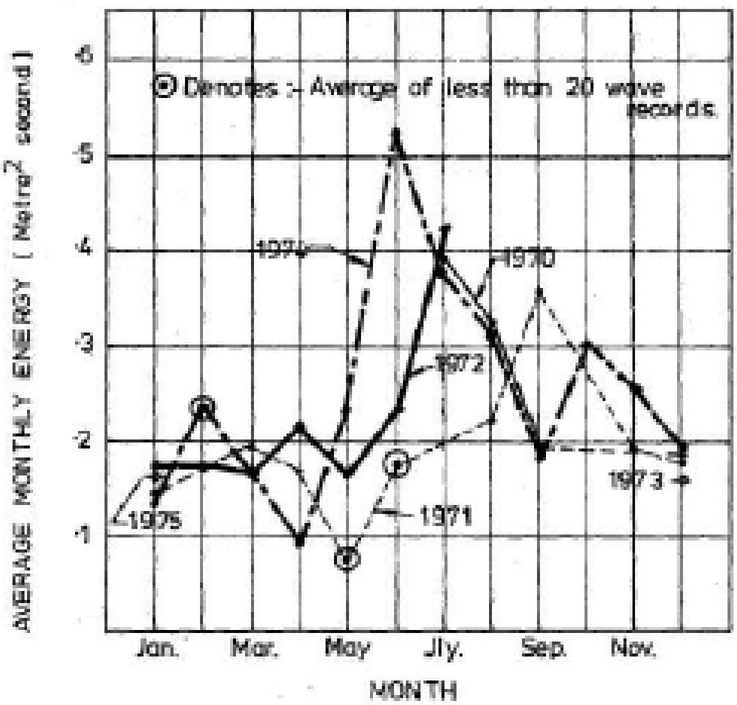


Figure 18 **Variation of Yearly Wave Climate (Garden Island 1970-1975)**
Extracted from Riedel & Trajer (1978)

3.4.2. Bunbury Wave Observations

During planning for expansion of Bunbury Port, a wave-rider buoy was deployed offshore from Bunbury from 1977 to 1981. The result of this deployment are summarised by Table 5.

Table 5 **Bunbury Extreme Wave Distribution 1977 to 1981**

Recurrence Interval	Tz Period	H1 Summer	H1 Autumn	H1 Winter	H1 Spring
1 year	9.4 s	4.1 m	6.4 m	7.0 m	5.4 m
2 years	9.7 s	4.4 m	7.1 m	7.7 m	5.8 m
5 years	9.9 s	4.9 m	8.2 m	8.5 m	6.4 m
10 years	10.2 s	5.5 m	9.4 m	9.5 m	7.1 m
30 years	10.4 s	6.1 m	10.8 m	10.6 m	8.0 m
50 years	10.6 s	6.5 m	11.5 m	11.0 m	8.5 m
100 years	10.8 s	7.0 m	12.8 m	12.0 m	9.3 m

The offshore buoy was deployed in water approximately 42 m deep. Two inshore deployments of waverider buoys also occurred in 1975-1976 and 1977.

Since 1994, Bunbury Port Authority has operated a waverider buoy or a bottom-mounted acoustic wave recorder as part of its dynamic under keel clearance system. Data from the bottom-mounted wave recorder has been made available for this study by the Authority (Figure 19 and Figure 20).

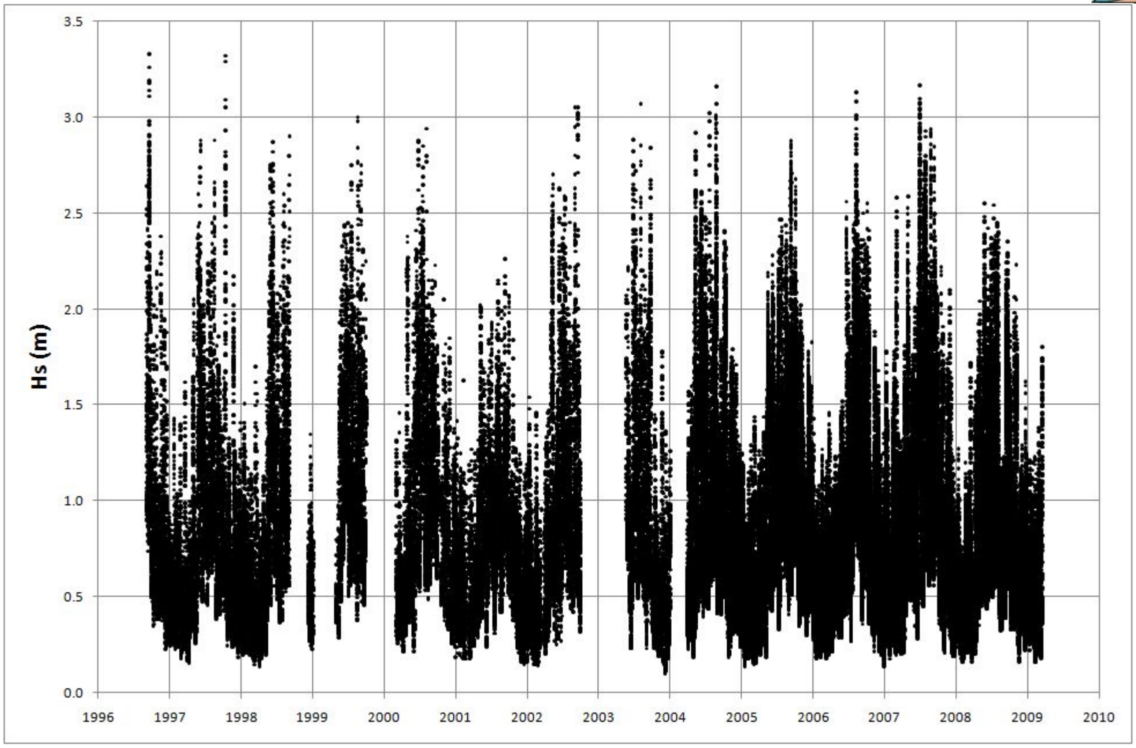


Figure 19 Bunbury AWAC wave record
(Source: Bunbury Port Authority)

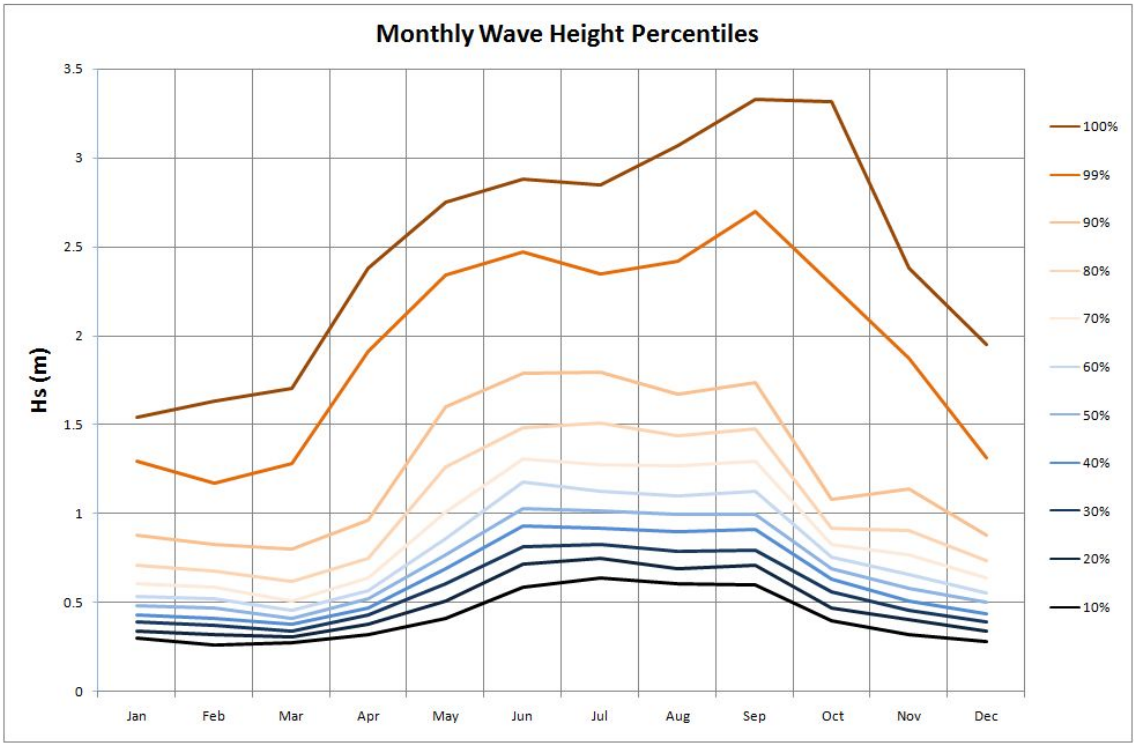


Figure 20 Seasonal frequency of wave height from Bunbury AWAC

3.4.3. Dawesville Wave Observations

Prior to construction of Dawesville Channel, a series of waverider buoy deployments were undertaken from 1985 to 1987 (Buchan *et al.* 1987). These provide some indication of wave conditions at the northern end of Yalgorup Coast (Table 6).

Table 6 Dawesville Extreme Wave Distribution (1985-1987)

Recurrence Interval	Location 22	Location 23	Location 24
Date	Apr-85 to Oct-86	Apr-85 to Aug-85	Apr-85 to Apr-87
Depth	25m	10m	10m
1 year	3.2 m	5.2 m	5.8 m
5 years	3.8 m	6.5 m	7.0 m
10 years	4.2 m	7.2 m	7.6 m

3.4.4. Offshore Wave Observations

A non-directional waverider buoy was installed offshore from Rottnest in 1993, in 48 m water depth. This instrument was upgraded to a directional waverider in 2004 (Department of Transport 2009). Analysis of the first three years of records from 1994-1996 showed a high ambient wave climate of approximately 1.5 m height and 7 seconds (T_{01} statistic) during summer, increasing to approximately 2.0 m height and 9 seconds periods during winter (Lemm 1996). The longer record from 1994 to 2006 shows high inter-annual variability of extreme waves, but the ambient summer-winter cycle remains relatively consistent from year to year (Figure 21).

A waverider buoy was deployed offshore from Cape Naturaliste in 1999, in 50 m water depth. The time series of observations (Figure 22) is consistent with the Rottnest record from 1999 to 2005, but shows different behaviour for 2006 and 2007 storm events.

Extreme analysis of the offshore wave records from Rottnest (1994-2007) and Cape Naturaliste (1999-2007) suggests more energetic wave conditions at the more southerly location (Figure 23). However, it is appropriate to note that extreme distribution strongly reflects by stormy periods and therefore is highly affected by inter-annual variability of the wave conditions.

Analysis of the directional wave record from 2006 only shows a broad directional range of high energy swell from 240^o to 280^o (Figure 24). This is a broader range than generally suggested by wave hindcasting, but retains a median west-southwest direction. Approximately 6% of the swell wave energy during 2006 arrived from north of west, but this only arrives during winter months. This confirms a net seasonal shift in swell direction described qualitatively for the Perth coastline (Masselink & Pattiaratchi 1998). However, analysis of synoptic system variability suggests that the quantity of change may vary significantly between years (Steedman & Associates 1982; Panizza 1983).

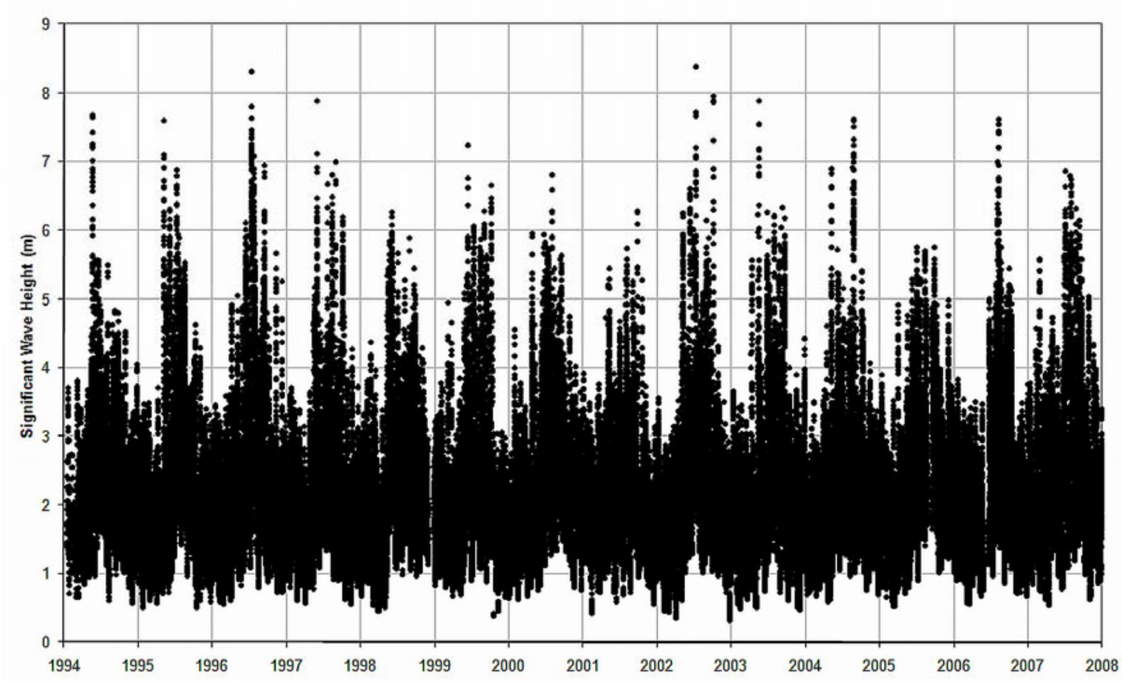


Figure 21 Rottnest Offshore Wave Height (1994-2007)

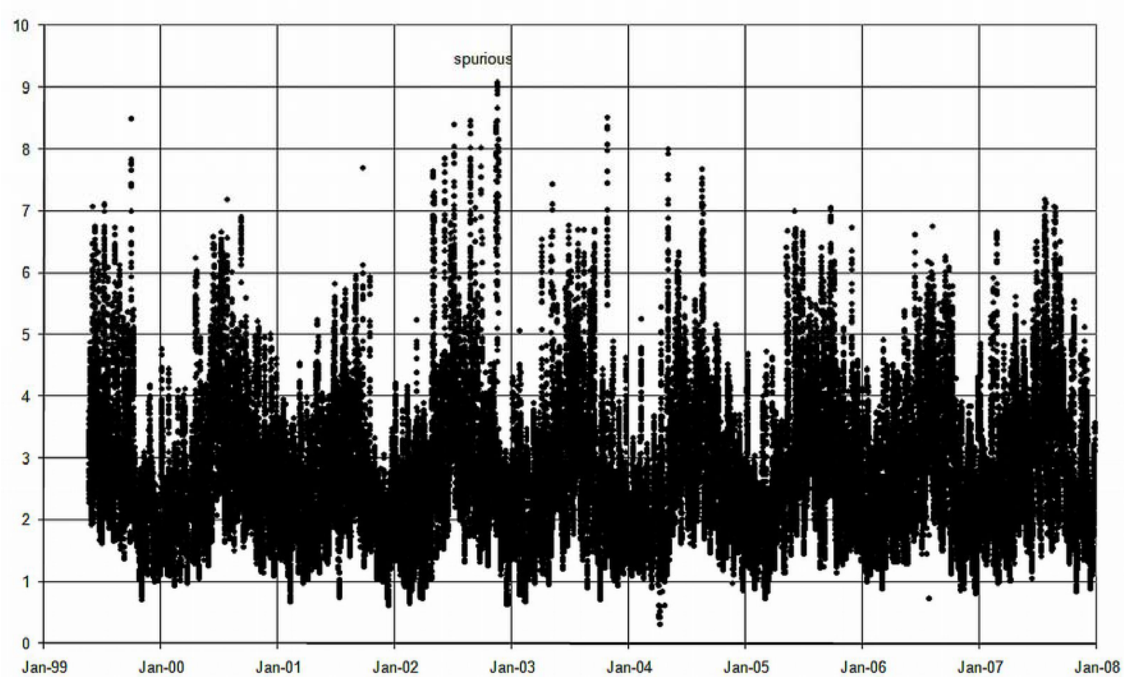


Figure 22 Naturaliste Offshore Wave Height (1999-2007)

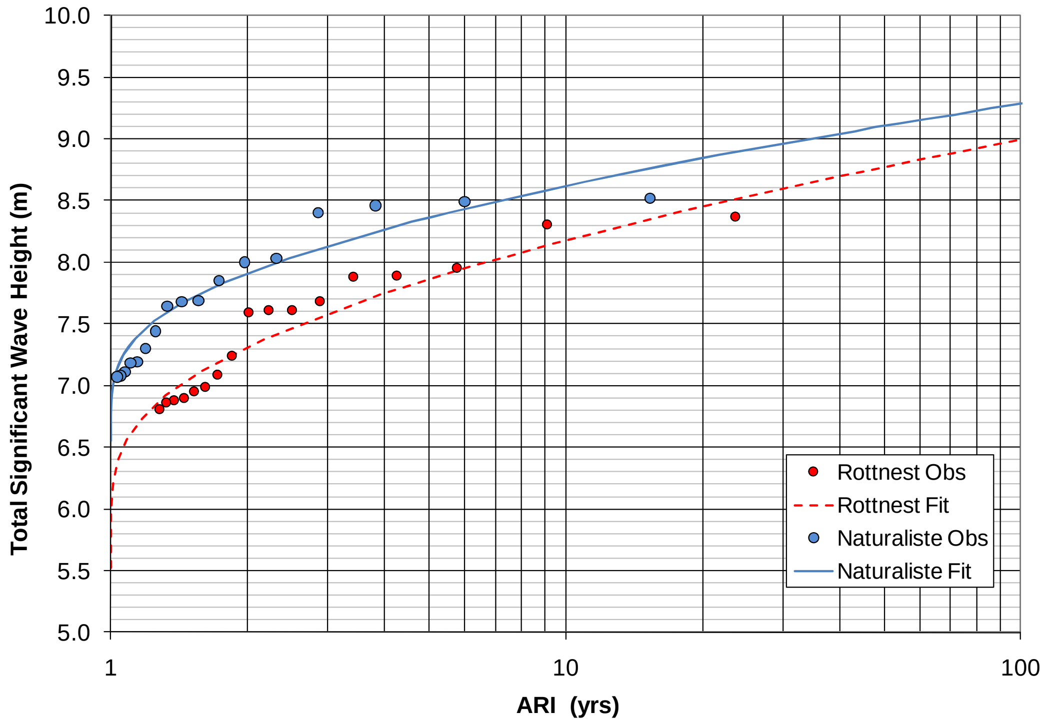


Figure 23 Offshore Extreme Wave Distributions (Rottnest & Cape Naturaliste)

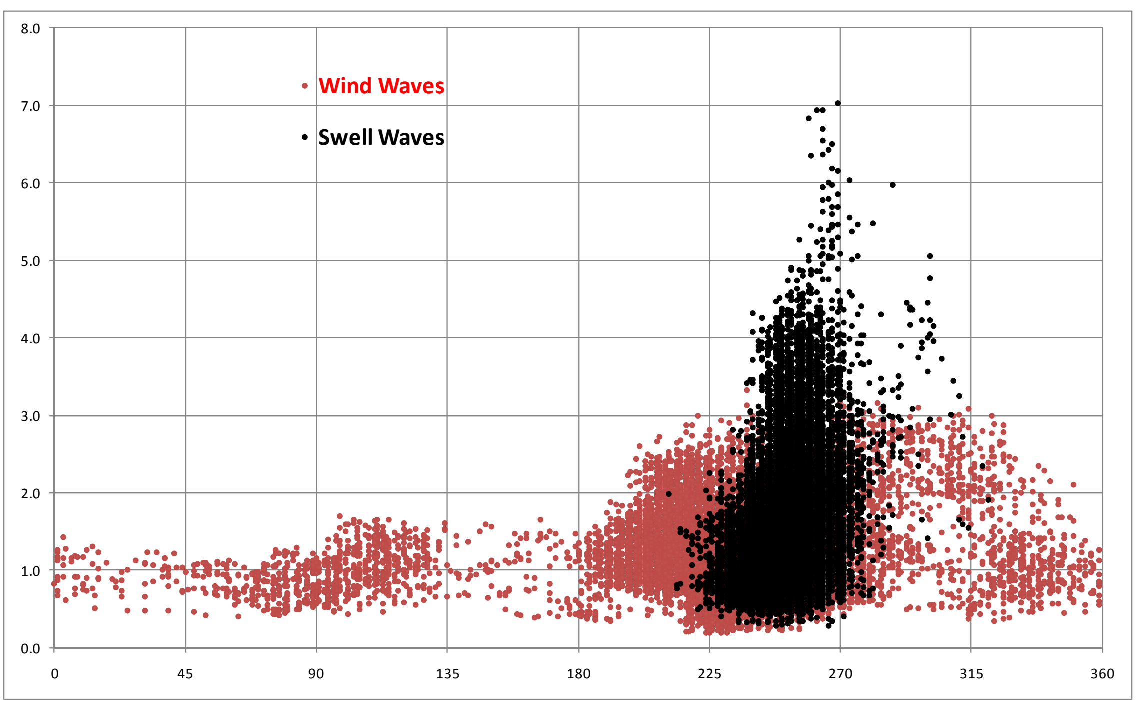


Figure 24 Wave Height and Direction at Rottnest (2006)

4. GEOMORPHOLOGY

Major landform components of the Yalgorup Coast have been described in several papers and environmental management plans, the latter including those summarised by CALM (1995) for the Leschenault Peninsula Management Plan and Belton-Taylforth (2006) for the Shire of Harvey. In a seaward sequence the main features (Table 7) describe a retrograding coastal sand barrier, the Leschenault - Yalgorup Barrier, comprising active and inactive parabolic dunes as well as the beach and shoreface (Hesp & Short, 1999b).

Formation of the 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 past 10,000 years and continuing at present. Following the nomenclature of Roy *et al.* (1994), the barrier system is episodically-transgressive with phases of dune activity leading to development of the dune ridge through the formation of foredunes, blowouts and nested parabolic sand dunes as the ridge migrates landwards. 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 shore between Cape Naturaliste and Cape Bouvard. Such low-frequency changes are difficult to determine from the short, available historical records of coastal change although they may be apparent in the stratigraphic record.

Coastal change on unconsolidated sedimentary shores is a function of interaction between morphology, sediments and oceanographic processes, with alteration of any single factor impacting on the other two. Hence shorelines of mobile sediment are constantly in a state of change, with the movement of waves and currents causing transport of sediment under all but the most quiescent conditions. The variations in weather conditions, sea level and the wave regime described above all impact on the coast to determine whether the coast tends to an accretionary or erosional state, or is relatively stable, at any time scale

Shoreline change is typically described in terms of cross-shore and alongshore sediment movement (van Rijn 1996). This 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 net 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 net annual sediment movement to alongshore transport. Although the distinction between cross-shore and alongshore transport is convenient, it is not altogether accurate, as significant alongshore transport also may occur pulsationally and over short times frames. Similarly, cross-shore transport may not always have a net zero change over years or even decades.

Cross-shore processes for the Yalgorup Coast are apparent in the historical record of shoreline movement compiled from interpretation of aerial photography by the Department of Transport (Byrne *et al*. 1987). It is also evidenced by the presence of significant shore parallel features in the nearshore waters, a scarped foredune and mobile secondary dunes where sediment is actively moving inland from the shore. The effect of alongshore transport is apparent through the geological structure of the Leschenault - Yalgorup Barrier, observed historic changes to the shoreline, and on the basis of estimated alongshore transport rates near Bunbury and Mandurah. The following analysis examines changes to the beach and coastal dune components discernable from the historical aerial photography and ground surveys. It provides an indication of the areas susceptible to change.

Table 7 Landform components of the Yalgorup Coast

(After Belton-Taylforth 2006)

	LANDFORM	DESCRIPTION
1	Salt flats or estuarine terraces	The back-barrier flats abut salt flats formed by estuarine sediments at the interface between the barrier and coastal lagoons. Oma (1989) noted the estuarine sediments also occur beneath the barrier dune system and, therefore, support Semeniuk's (1983) assertion there is an eastward migration of the barrier dune system.
2	Sand plains or back-barrier flats	The sand plains or back-barrier flats occur along the eastern margins of the dune barrier. They have been interpreted as being formed during the Holocene period (Semeniuk & Meagher 1981; Oma 1989) at a time when sea level was slightly higher than at present and the barrier was forming.
3	Vegetated parabolic dunes	McArthur & Bartle (1980) recognised four age classes within the vegetated parabolic dunes. The youngest (termed Q4) are relatively small and steep sided. Soils are deep, calcareous and with minimal humus development. The oldest (termed Q1) occur along the eastern margin of the dune barrier and are more ribbon to crescent shaped. They are lower in profile, have more gentle slopes and more pronounced soil development (Oma 1989).
4	Mobile dunes	Mobile dunes or blowouts are actively east-west moving parabolic dunes that engulf the vegetated parabolic dunes (Trudgen 1984; Oma 1989). Blowouts occur as discrete entities in the northern section of the coast. In parts of the southern section they have merged to form mobile sand sheets.
4	Deflation basins	Deflation basins are small, hollows and commonly occur as dune slacks within parabolic dunes close to the shore. Soil development is variable as is the vegetation cover, with bare sand being apparent in the active dunes.
6	Foredunes	Foredunes are the first stage of dune formation. They support pioneer vegetation communities and are usually present as a single ridge at the landward, eastern margin of the beach.
7	Beach	The beachface is generally steep and has been classified as a wave reflective beach by Short (2005), although the steepness is also likely to be a response to the strong longshore currents generated by the prevailing SW winds. The shoreline and beach is considered to be retreating eastward at an estimated rate of up to 2 m a year.
8	Shoreface	The shoreface is area dominated by wave action and longshore transport. It is sand-mantled and slopes gently westwards to merge with the inner shelf plain about 1-2km from the shore in water depths of 12-15 metres. Areas of limestone exposed limestone, outliers of beach rock and outliers of estuarine mud protrude through the sandy veneer in several places on the inner shelf plain and shoreface. These form the geologic framework within which the shore has developed.

4.1. LITTORAL TRANSPORT

The Yalgorup Coast is part of a primary sediment compartment extending from Cape Naturaliste to Rottnest Island. Within this compartment it constitutes an almost north-south aligned coast running between Bunbury and Mandurah, with Casuarina Point at Bunbury and Robert Point near Mandurah forming natural boundaries to a large sediment cell, referred to here as the Yalgorup cell. Smaller sediment cells, named for their proximity to local settlements or landscapes, are nested within the large cells. Their structure and function is determined by local variation in the geologic framework, particularly the proximity of sub-tidal limestone pavement to the shore. The stability of the coast is a function of sediment movement in the littoral zone, the area including the active beach and shoreface (Figure 25). Sediment movement may be considered at a broad scale within the compartment and around the shores of Geographe Bay, more locally as sediment movement between Casuarina Point and Robert Point, or at a finer scale. All three scales are important to any appraisal of risk. Movement of sediment within the compartment directly determines the volume of sediment supplied to the Yalgorup cell from south of Bunbury and offshore. The structure of the Yalgorup cell, with its variation in aspect and exposure to metocean processes, establishes broad geographic variation in barrier and beach morphology. In turn the response of the local cells to fluctuations in the volume of sediment being moved along the coast is geographically variable and provides an indication of the relative stability of different parts of the coast.

The sediment cell including Yalgorup Coast is largely unprotected by offshore reefs, allowing the prevailing southwest offshore swell to dominate the coastal sediment transport and producing a net northwards transport of material, although occasional northwest winter storms may reverse the net pattern of transport. The principal sources of sediment being moved along the coast include sediment moved landward off the continental shelf during the Holocene rise in sea level, modern bioproduction of material in the seagrass meadows and reefs of Geographe Bay, erosion of dunes south of Bunbury and within the Yalgorup cell, as well as reworking of beach material. As described above, sediments are transported along and across the shoreface and beach. Much of the transport occurs on the dry beach during periods of onshore wind activity, particularly the strong sea breezes of the region. Sediment is lost from the shoreface and beaches of the compartment and cell at places where it is moved landward, forming dunes and aiding their migration; where sediment is transported into estuaries via entrances such as the Leschenault Inlet Cut and the Dawesville Channel; and where it is moved offshore into deep water beyond the active shoreface. The volumes of sediment associated with each of these components of these components of the sediment cell have not been measured. However, the volume of material being moved in the littoral zone may be approximated from estimates of sediment accumulation at Bunbury, Dawesville and Mandurah.

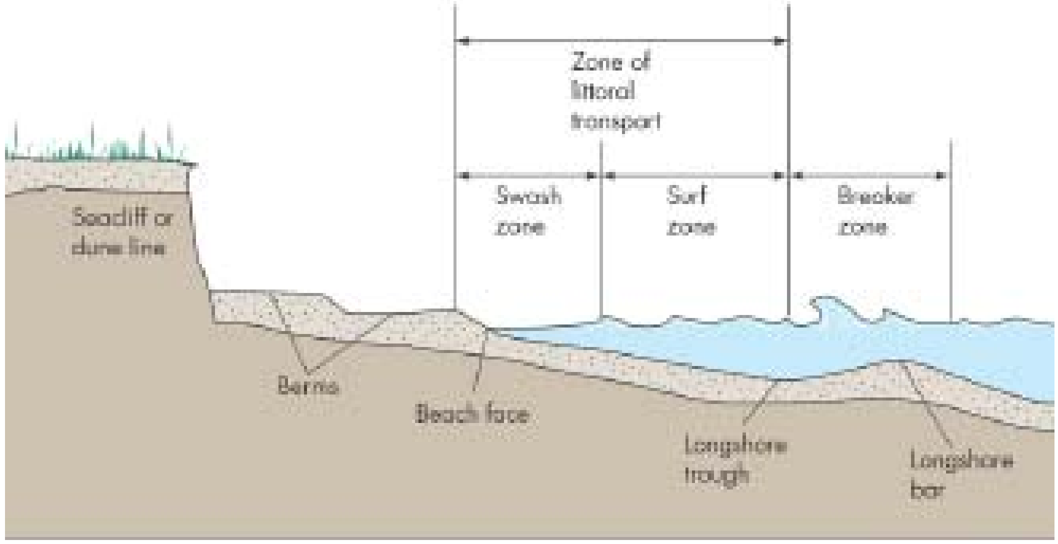


Figure 25 The littoral zone of a sandy beach

4.1.1. Sediment Accumulation at Bunbury

Breakwaters for Bunbury Harbour were built as a series of works from 1896 to 1961 to reduce the quantity of sand arriving from the south side of Casuarina Point. An additional groyne was constructed near the former Power Station site in 1934 to prevent occasional incursions of sand from the north. The Port deepwater channel has been maintained by dredging since the 1960s. The Port breakwaters and deepwater channel significantly restrict littoral supply to the north (Byrne *et al.* 1987). However, it should be noted that offshore spoil disposal is likely to return sediment to the beaches further north, and a small quantity of natural bypassing is likely to occur.

Historical estimates of littoral transport have been made through analysis of dredging records for the head of Bunbury Harbour Breakwater (PWD 1978; Byrne *et al.* 1987). These suggest a net longshore sediment transport rate varying from 55,000 to 80,000 m^3 per year. However, records from the wider port area suggest a greater quantity of material accumulates, with an average of 210,000 m^3 per annum from the harbour and deep channel (

Table 8). Although some of this material may be related to developmental dredging, it is significantly greater than the quantity previously removed from the breakwater sand traps.

Due to the nature of the sand trap and the deep channel, the dredging rates effectively form an upper and lower bound for the quantity of littoral transport. The sand trap fails to identify natural bypassing or transport reversals and therefore is a lower bound estimate. The deep channel may act as a local sink for sediment and has the capacity to capture gross material transport in either direction. As such, it represents an upper bound for the littoral transport rate.

Table 8 Previous Dredge Volumes – Bunbury Port Authority

1988	340,000 m^3
1990	520,000 m^3
1990	107,000 m^3 (short dredge campaign Sept)
1994	416,518 m^3
1997	656,000 m^3
2001	665,500 m^3
2004	506,354 m^3
2006	30,000 m^3 (short campaign Feb)
2007	37,750 m^3
2007/08	600,000 m^3
2008	166,600 m^3
2008	235,900 m^3

Bunbury Port Authority data obtained from Shore Coastal (2009).

4.1.2. Accumulation at Mandurah and Dawesville

At Mandurah, Roberts Point defines a sharp change in coastal aspect, with a broad shallow area of coastal limestone. The change in aspect enables release of northward littoral transport during summer months, depositing it as a large spit at Robert Point. Winter storms push this deposition eastwards towards Mandurah Channel. Prior to construction of training walls at Mandurah, the sediment transport fed into a net northwards transport along the shore of Comet Bay. Since the 1980s, sediment transport between Mandurah Channel and San Remo has been highly modified, including annual use of sand bypassing plant to shift material from the west to east side of Mandurah Channel. Approximately 100,000 m^3 is bypassed each year.

Since 1994, littoral transport has also been interrupted through artificial management at Dawesville Channel, approximately 11km south of Mandurah and closer to Cape Bouvard. Training walls and a spur groyne are used to trap the net northwards sediment transport, which is mechanically bypassed to the north side of the channel. Approximately 85,000 m^3 is bypassed each year. Annual beach monitoring associated with the bypassing contract has identified variability in the deposition patterns within the sand trap (Bicknell 2006). Elevated conditions of wave or water level produce a higher beach berm and consequently a narrower beach for the same given volume. Under low conditions, the broader beach reduces the capacity that the spur groyne holds before bypassing occurs.

4.2. MODELLED SEDIMENT TRANSPORT

Several exercises to estimate alongshore sediment transport rates on the basis of wave climate have been undertaken. The most studied area has been Bunbury Back Beach, due to ongoing coastal management issues (DMH 1990; Port & Harbour Consultants 2000). However, the most relevant analysis has been undertaken along the Bunbury to Mandurah coast, as part of Dawesville Channel coastal process investigations (Paul & Hutton 1985; Byrne *et al.* 1987)

Estimates of sediment transport for the Bunbury to Mandurah coast (Table 9) made distinction based largely upon coastal aspect. The calculated potential for littoral drift was subsequently scaled to match the observed quantity of material dredged at Bunbury Harbour.

Table 9 Modelled rates of sediment transport: Bunbury to Mandurah

Location	Modelled Transport (m^3 p.a.)	Scaled Transport (m^3 p.a.)
Bunbury	105,000 m^3	80,000 m^3
Leschenault	85,000 m^3	65,000 m^3
Preston	50,000 m^3	40,000 m^3
Dawesville	200,000 m^3	150,000 m^3
Roberts Point	100,000 m^3	75,000 m^3

These quantities are significantly greater than estimated for Bunbury Back Beach using similar modelling, which calculated 22-53,000 m^3 p.a. transport (DMH 1990). However, it is recognised that this approach provides a relatively coarse estimate for littoral transport, as it cannot resolve local scale features (Byrne *et al.* 1987).

It is noted that the estimates of alongshore sediment transport are highly sensitive to wave direction and period. Consequently, both high energy swell waves, and directionally variable wind waves (Figure 24) can be significant to the overall transport rate.

4.3. LANDFORMS & COASTAL CHANGE

Five sediment cells are nested within the main Yalgorup cell. Their boundaries are discernible in plan-form as low-amplitude salients associated with wider than average rock pavements and ridges in the nearshore waters, whereas the cells are shallow embayments (Figure 4). The cells are open, with sediment movement readily possible between adjacent cells. The landforms of each cell are described in three map series (Appendix 1 & Attachment 1 - DVD) containing the following information:

Series 1	Orthophoto; Bathymetry; rock occurrence (mapped from orthophoto and photos taken from helicopter survey); (DVD Name = cellX_s1geobath.pdf)
Series 2	Orthophoto; rock occurrence (mapped from orthophoto and photos taken from helicopter survey); and dune sequence (morphology following terminology reported by Hesp in Short 1999) (DVD Name = cellX_s2geodune.pdf)
Series 3	Orthophoto; long-term foredune movement (estimated by comparing the 1955 vegetation line with the vegetation line on the orthophoto); and long-term sand drift movement (captured by comparing the 1955 sand drift kine with the blowouts on the orthophoto). (DVD Name = cellX_s3sedmove.pdf)

4.3.1. Landforms

Inshore Rock Outcrops

The geological framework includes subtidal rock pavement, elongate ridges and rock platforms (Figure 26; Appendix 1A). Pavement is more prevalent on the seabed in extreme southern and northern parts of the Yalgorup Coast, with the most extensive pavements forming the boundaries of the primary cell in the vicinity of Binningup and near White Hills Road. Although of low-amplitude, significantly shoreline salients of unconsolidated sand occur landwards of the rock pavements at Binningup and Cape Bouvard. Together with the rock pavement they form natural obstacles to littoral transport along the shore. The rock pavement is patchier with distance north from Binningup and includes distinct linear ridges in the nearshore waters of Cells 2 to 4 (Lake Preston South, Preston Beach and Lake Clifton North) and as rock platforms along the shoreline in parts of the two northernmost cells (Lake Clifton North and White Hills Road). Rock pavements and ridges also contribute to formation of the smaller low-amplitude salients constituting the three boundaries of the five local sediment cells between Binningup and Cape Bouvard. Occasionally rock also outcrops in the supratidal zone at the landward side of the beach and in the dunes.

	**a. SANDY NEARSHORE** (Photo; Bob Gozzard - Coast Run 032) Sandy seafloor dominates the nearshore although scattered rock outcrops occur in the inshore zone along the southern part of Cell 1 – White Hills Road. Here the beach is backed by a scarped hummocky foredune ridge and partially vegetated blowout dunes overlying nested, vegetated blowouts
	**b. ROCK PAVEMENT, WIDE CHANNEL & BEACH** (Photo; Bob Gozzard - Coast Run 026) A wide channel (>20m) running along the inshore separates the rocky pavement from the beach. This pavement, near White hills Road, is large and associated with at foreland at Cape Bouvard. The beach is backed by a low hummocky foredune ridge a narrow ridge of active blowouts and nested, vegetated blowouts
	**c. ROCK PAVEMENT, NARROW CHANNEL & BEACH** (Photo; Bob Gozzard - Coast Run 107) Rock outcrops as a narrow ridge close to the shore in Cell 4 – Lake Preston South. A narrow channel separates the ridge from a scarped beachface. The beach is backed by a discontinuous hummocky foredune ridge, active coalescing blowouts and vegetated parabolic dunes.
	**d. BEACH ON ROCK PLATFORM** (Photo: Gary Whisson – P3060083) Beach directly overlies rock platform in the northern part of Cell 1 – White Hills Road. The elevation of the platform is close to low tide level such that rock is exposed with wave run-out. The beach is narrow and backed by a scarped, hummocky foredune, and vegetated blowouts overlying nested, vegetated blowouts and parabolic dunes.

Figure 26 Inshore rock outcrops and proximity to the shore

The Beach

Short (2005) classified the beach along the Yalgorup Coast as being reflective, which implies a narrow berm, steep beachface (5^o to 10^o), absence of nearshore bars and relatively deep nearshore waters. These geometric characteristics are apparent in Figure 27. Reflective beaches are commonly comprised of coarse sand and subject to a modal swell wave regime of less than 1.0 m significant wave height. Waves break at the shore with much of the energy returning seaward as a reflected wave that begins as backwash run-out from the beachface. Because they are at the lower end of the spectrum describing wave dominated beaches such beaches may be subject to a high degree of variability with fluctuations in water level and the wave regime.

Figure 27 Myalup Beach

View south along Myalup Beach showing a scarped berm, beachface with cusps and waves breaking at the shore. The steep beachface and shore break are characteristic of reflective beaches.

Shoreline Movement 1955 to 2006

Gross change along the shore was estimated by comparing the 1955 vegetation line mapped from rectified aerial photography by the Department of Transport (then the Department of Marine and Harbours) with the vegetation line on the orthophoto map compiled from 2006 photography. The change should only be considered as indicative of shoreline movement because differences between the two sets of photographs may reflect short-term conditions at the times of photography rather than a sustained trend. This results from a naturally highly-variable coastal climate. Rates of change should not be estimated from the data available. Despite this the results (Appendix 1C) do show change in the position of the vegetation line and for this reason they are described as foredune rather than shoreline movement in Appendix 1C. Value in establishing change in the vegetation line along the back of the beach is to provide a geographic comparison of the changes against the geologic framework and the activity of blowouts in the primary dunes.

Overall, the pattern of change between Binningup and Cape Bouvard is consistent with the prevailing SW winds, exposure to the SW swell regime and northerly littoral drift with the coast being eroded in the southern sector and accretion, albeit discontinuous, more commonly occurring to the north. The alternation of reaches of erosion and accretion in the northern sector apparently is related to local variation in the geologic framework and its localised affects on littoral processes.

Beach erosion is common throughout the two southern cells (Myalup and Lake Preston South). In Cell 3 -Preston Beach the erosion continues into the lower third of the cell but the foredunes have apparently accreted in the vicinity of the shoreline salient marking the northern boundary. A recurrent pattern of accretion occurs in the two northern most cells (Lake Clifton North and White Hills Road) with the northern flank of salients undergoing accretion and the northern ends of the cells erosion. This is a reversal of the overall pattern in the primary cell, but is not considered likely to reflect a reversal of sediment transport direction. Instead, it suggests localised migratory behaviour of sediment around the smaller salients under weak to moderate SW wind conditions, such as periods of prolonged sea breeze activity.

Dunes

Dunes of the Leschenault -Yalgorup Barrier are comprised of Safety Bay Sand, Holocene calcareous and quartzose sands derived from the beach and foredunes. They are perched on an older Pleistocene basement comprised of Tamala Limestone and partially lithified lacustrine sedimentary units close to or slightly above present sea level. The exact elevation and geographic variation in occurrence of the older surface is unknown but requires determination if the full significance of the geologic framework as a factor determining coastal stability is to be thoroughly understood. The Holocene dune barrier is not wide and outcropping of the limestone directly affects beach and foredune stability. It is likely therefore that the basement affects the stability and distribution of dunes along the coast.

Three sets of Holocene dunes have been distinguished in Appendix 1B: foredunes, primary dunes and secondary dunes. The distinction broadly follows that of McArthur & Bartle (1980) and Oma (1989) but combines the more stable forms (Q3 & Q4) they identified. The description used here is intended to highlight short, intermediate and long-term susceptibility to environmental change. Foredunes are shore-parallel ridges of wind-deposited sand trapped within vegetation along the landward margin of a beach. They are highly dynamic and susceptible to change. Primary dunes are identified as the first line of transgressive (mobile) dunes, blowouts and parabolic dunes, migrating landwards from the shore. Again they are dynamic, especially where there is no vegetation cover. For convenience of description the secondary dunes include all dunes to landwards, particularly dune ridges as well as nested blowouts and parabolic dunes covered with vegetation. More detailed analyses and description of these landforms have been provided by McArthur & Bartle (1980) and Oma (1989). They are the most stable of the three dune units described in Appendix 1B.

The initial accumulation of beach sand in foredunes is a loss to the littoral sediment budget. The loss may be temporary (short-term) if the foredune is eroded by ocean processes during storm events and rebuilt afterwards, or more permanent (long-term) when the foredune is destroyed by onshore winds and its sediment blown further landward to form blowouts and parabolic dunes. Descriptions of foredunes reviewed by Hesp (1999a) include distinction between incipient (newly developing) and established forms, as well as their state of accretion, stability or erosion. Their descriptions have been loosely followed in assessing landform changes along the Yalgorup Coast. An objective has been to identify areas where the foredunes dunes are absent; have been scarped (a cliff or cut) by coastal erosion; are of low or high development; or have formed small plains of parallel ridges. Foredunes associated with accretionary and erosional states are shown in Figure 28 and their distribution illustrated in Appendix 1B.

The state of the foredunes is linked to sediment supply, the geological framework, antecedent dune morphology and the type of vegetation growing along the backshore. Their state is also likely to be linked with groundwater availability for plant growth. Low, discontinuous, hummocky dunes are common in the southern two cells (Myalup and Lake Preston South) in which the dune barrier is narrowest. They are higher in the Preston Beach cell (Cell 3) especially near the northern boundary where they have formed along the seaward margin of a large deflation basin. Foredune morphology is more variable in the northern cells, Lake Clifton North and White Hills Road. Some sections of the northern cells lack foredune and others landwards of rock platforms have erosion scarps. In contrast to the eroded foredunes, a narrow foredune plain is apparent as an inset at the southern end of the White Hills Road cell (Cell1). The variability of form is associated with breakdown of the foredune ridge through blowout formation (Appendix 1C) but is not always consistent with the pattern of beach erosion indicated by change to the vegetation line along the backshore.

The common features of the barrier are blowouts and parabolic dunes (Figure 28); the former saucer shaped and the latter elongate depressions with training arms bordering dune slacks (depressions). The advancing front of both is a high asymmetrical wedge of sand with a steep slip-face spilling over any obstacles encountered as it migrates landwards (Hesp 1999a). Other dunal features of the Yalgorup Barrier include fields of nested blowouts and/or parabolic dunes comprising the main ridge; coalescing blowouts where several mobile dunes are in the process of combining; mobile sand sheets where the combined dunes are moving freely as a single landform; and deflation basins which are extensive hollows remaining where sand sheets and/or coalescing blowouts have become detached from the shore. All are present as vegetated (stable) and unvegetated (mobile) forms.

Active blowouts and tracts of partially vegetated dunes, those with less than approximately 50% cover, occur in all sediment cells. The most extensive areas are landward of deflation basins in the northern sectors of Lake Preston South (Cell 4) and Preston Beach (Cell 3), on the southern flanks of the salients at the cell boundaries. Other active blowouts in the primary dunes occur close to beach access tracks in Cell 2 – Lake Clifton North as well as near the outlet of the Harvey Drain and as small individual or coalescing blowouts in Cell 5 – Myalup.

In contrast to these areas, narrow hummocky plains and narrow foredune plains are apparent in the two northern cells (Lake Clifton North and White Hills Road). In both locations they form part of the northern flank of the salient identifying the cell boundary. Both are indicative of recent accretion, the former as rapid infill of an eroded inset and the latter sequential development of a series of foredune ridges. Although their mode of formation is a function of the type of pioneer vegetation trapping sediment transported by onshore winds their location appears to be linked with the localised migratory behaviour of sediment around the smaller salients identified from the pattern of shoreline movement.

	**Incipient foredune & high foredune ridge** (Photo; Bob Gozzard - Coast Run 055) A low, incipient foredune has formed on the backshore, seaward of a high, vegetated foredune ridge in Cell 3 – Preston Beach. The incipient dune and vegetated foredune have reduced the sand supply from the beach to the partially vegetated blowouts to landward.
	**Low hummocky foredune ridge** (Photo; Bob Gozzard – Coast Run 107) A low hummocky foredune has developed along the backshore of the beach and on the seaward side of a partly vegetated ridge of blowout dunes in Cell 4 – Lake Preston South. The shape of the hummocks is associated with the growth habitat of the pioneer vegetation covering the hummocks.
	**High hummocky foredune ridge** (Photo; Bob Gozzard - Coast Run 068) In the north of Cell 3 – Preston Beach a high hummocky foredune ridge has formed on the backshore, seaward of a deflation basin and a partly vegetated high ridge of blowouts. Evidence of small blowouts being active in the early, incipient phase of ridge development is apparent as low lobes of white sand intruding onto the surface of the depression.
	**Foredune plain** (Photo; Bob Gozzard – Coast Run 061) A low hummocky foredune ridge is backed to landward by a series of vegetated foredunes in Cell 2 – Lake Clifton North The plain is indicative of an accretionary phase of foredune development through pulsatory transport and little aeolian reworking of the foredune sediments as each foredune ridge develops.

Figure 28a Foredunes: accretionary states

Foredune development is the first stage in formation of dunes through accumulation of wind-blown sediment in vegetation at the landward margin of the beach. The photographs show accretionary phases of foredune development.

	**Discontinuous and partly vegetated hummocky foredune ridge** (Photo; Bob Gozzard - Coast Run 099) Foredune ridges begin as isolated hummocks formed when sand is trapped by pioneer vegetation. The hummocks may ultimately coalesce to form a ridge and in so doing cut off the sand supply to active dunes in the hinterland of Cell 4 – Lake Preston South or they break down and contribute sediment to the blowouts.
	**Scarped hummocky foredune ridge** (Photo; Bob Gozzard – Coast Run 035) Along this part of Cell 1 – White Hills Road the foredune has been cut by beach erosion leaving a low sand cliff along the backshore. Wind funneling landwards between vegetated hummocks may further exacerbate erosion of foredune ridge and reactivate the partially vegetated blowouts forming the primary dune ridge.
	**No foredune** ((Photo; Bob Gozzard - Coast Run 055) Although some vegetation is on the scarp face the foredune has been eroded and the primary dune cut in the central part of Cell 2 – Lake Clifton North Incipient blowouts apparent along the crest of the primary dune ridge may be a first stage of primary dune destabilization if they are not colonized by pioneer vegetation.
	**No foredune. Sand feed from beach to active blowouts** (Photo; Bob Gozzard – Coast Run 053) In the central part of Cell 2 – Lake Clifton North sections of foredune have been eroded and sand blown off the beach contributes to the active blowouts. This is a more advanced stage than that shown in the photograph above. Sand is lost from the sediment cell and the blowout ridge grows and rolls landwards.

Figure 28b Foredunes: erosional states

Destruction of the foredunes by beach erosion, wind scouring or excessive tracking through them contributes to destabilisation and landward migration of the primary dunes.

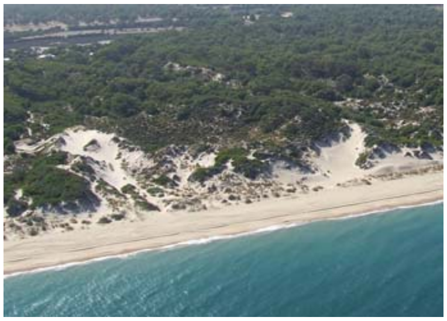
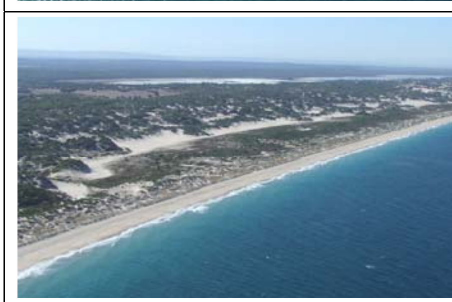
	**Small active blowouts** (Photo; Bob Gozzard - Coast Run 119) A discontinuous hummocky foredune fronts small active blowouts near the Harvey Drain in Cell 5 – Myalup. The blowouts are nested in older vegetated blowouts and form a narrow ridge on this part of the dune barrier.
	**Large active blowouts** Photo; Bob Gozzard - Coast Run 112) A high blowout dune migrating across the barrier ridge in Cell 5 – Myelup extends almost onto the backbarrier flats adjoining Lake Preston. . The parabolic blowout has been modified where it has buried older vegetated dunes and is partly cut off from the beach sand supply by the hummocky foredune.
	**Active coalescing blowouts** (Photo; Bob Gozzard - Coast Run 115) Active blowouts landward of a discontinuous foredune ridge in Cell 5 – Myalup are coalescing as they transgress the older vegetated parabolic dunes to landwards. Remnant knolls of vegetated dune form ridges that separate the dune slacks and contribute to the parabolic form of the blowouts.
	**Sandsheet (mobile)** (Photo; Bob Gozzard - Coast Run 098) Coalescing blowouts have merged in to form a mobile sand sheet in Cell 4 – Lake Preston South immediately landward of a discontinuous foredune ridge. The sandsheet and blowouts it feeds are transgressing vegetated parabolic dunes further inland.
	**Deflation basin** (Photo; Bob Gozzard - Coast Run 098) A high hummocky foredune fronts a broad deflation basin in Cell 4 – Lake Preston South. The basin has formed as a mobile sand sheet migrated landwards to overwhelm older dunes and form a high ridge of partially vegetated dunes.

Figure 29 Active primary dunes

Areas of high vegetated dunes are located at four places along the barrier: in the north of Cell 5 (Myalup); landward of a narrow deflation basin in the south-central part of Cell 4 (Lake Preston South); again associated with a deflation basin in Cell 3 (Preston Beach); and the central part of Cell 1 (White Hills Road). The relationship of these areas to the underlying geologic framework warrants closer investigation. Three occur in close to the unstable shoreline areas associated with the cell boundaries. The exception is the area in Cell 1, which is close to the northern limit of Lake Clifton. The barrier is narrower as well as lower and between the areas of high dune.

4.3.2. COASTAL STABILITY

The various components of the coastal dunes comprising the Leschenault – Yalgorup Barrier should not be viewed as being separate entities. The barrier is a single unit and its different types of dunes are interactive. With sea level rise and over time, sands from formerly vegetated dunes commonly are incorporated in active dunes and reworked as the barrier is rolled landwards to transgress the lagoonal features of the hinterland. Unfortunately, the rates and sequence of dune transgression cannot be estimated without detailed radiometric dating and mapping of the stratigraphic units. However, the landforms and their distribution indicate change is neither steady nor evenly distributed along the coast; and that change is closely tied to the geologic framework structuring the barrier particularly rock outcropping close to shore and possibly underlying it. Further, more detailed investigations are required to test this proposition.

Long and Medium Term Changes

The Yalgorup Coast is subject to continual change and has been changing since assuming its present form approximately 7,000 years ago. A geologically structured compartment extending from Cape Naturaliste to Rottnest Island has provided topographic control for formation of an episodically-transgressive barrier, the Leschenault - Yalgorup Barrier, which supports the present coast. The barrier is a Holocene dune ridge perched in parts on a basement of lithified Pleistocene sediments that provide a framework for its evolution and change. The coast has been influenced in two ways by the geological framework. First, the underlying platforms have dictated littoral sediment transport and determined the nature of the shoreface profile as the barrier retreated to landward; and second, they modified and continue to modify incoming energy regimes, affecting the patterns of erosion, transport, and deposition on the adjacent shorelines.

Barrier evolution is continuing at present as sediment is moved along and across the shore. Phases of dune activity associated with fluctuations in the intensity and duration of metocean processes continue to contribute to development of the dune ridge through the formation of foredunes, blowouts and nested parabolic sand dunes as the barrier migrates landwards. 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 shore between Cape Naturaliste and Cape Bouvard. Such low-frequency changes are difficult to determine from the short, available historical records.

The main mechanism for barrier retreat is consistent with that described from other locations (Roy *et al*. 1994; Hesp 1999). Sediment accumulates on the beach where it contributes to the formation of foredunes. Destabilisation of the foredunes through natural biophysical processes leads to the development of blowouts, which may coalesce to form mobile sand sheets or migrate landwards as elongate, parabolic dunes. These forms continue to draw sediment from the shore for as long as they are connected to it and remain active. As they move landward they overwhelm pre-existing landforms and create an uneven shore-parallel ridge – the barrier. Migration of the mobile dunes may be temporarily halted by redevelopment of a new foredune that cuts off the sand supply from the coast until such time as the new foredune becomes destabilised and a new phase of blowout commences. In the intervening period, which may have taken 50 to 100 years, the hollow between the dunes migrating landward and the emergent foredune survives as a deflation hollow.

Recurrence of the cycle of dune formation and migration on the Leschenault – Yalgorup Barrier is ultimately dependent on sediment supply from offshore and alongshore. At present the alongshore component of littoral sediment transport between Binningup and Cape Bouvard is critical to coastal stability and future evolution of the barrier. This is indicated by the record of shoreline movement estimated from the 1955 and 2006 aerial photography showing changes in the position of the vegetation line, with erosion in the southern part of the embayment and accretion more common in the north. The ramifications of this are that the future medium-term stability of the Yalgorup Coast will potentially be affected by any updrift interference with the coastal sediment transport between Cape Naturaliste and Cape Bouvard as well as by natural variability and change to metocean processes.

Short Term Changes

Interaction of modern metocean processes with the inherited geologic framework has two ramifications. First, it produces localised reversals of the overall erosion-accretion pattern along the shore, consistent with local migratory behaviour of sediment around the smaller salients, such as may be caused by periods of prolonged sea breeze activity, with weak to moderate SW wind conditions. Alongshore variation in beach erosion, foredune formation and dune development occurs as a result of this interaction, with the most unstable reaches of coast in commonly in close proximity to shoreline salients and extensive submerged rock outcrops. Second, it may invalidate application of the Bruun Rule (Bruun 1988) that has been widely applied in the calculation of setback to development on mixed sandy and rocky coast in Western Australia (WAPC 2003). Under the Bruun Rule an allowance of 1.0 m of horizontal setback is made for each 1 cm of sea level rise, a 100:1 allowance. This is a gross oversimplification to the point of being misleading when applied to an area such as the Yalgorup Coast where substantial localised changes may exceed and run counter to broader scale patterns.

Despite the lack of detailed morphostratigraphic and chronologic information, the following general observations about coastal change and stability can be summarised from the available data:

1. Bathymetry in Cells 4 and 5 (Lake Preston South and Myalup) has only a narrow section of shallow water (0 – 10 metres) before deepening to 10 – 20 metres. This coincides with the dominantly erosive environment immediately north of the rocky pavement off Binningup in the southern part of Cell 5 (Myalup).
2. Cells 1 and 2 (Myalup and Lake Preston South) have a broad area of shallow inshore water, coinciding with a more depositional inshore environment. The inshore waters of Cell 3 (Preston Beach) appear to be transitional with the narrow, shallow section of the southern cells beginning to deepen.
3. Comparison of changes to the vegetation line along the beach backshore from 1955 to 2006 indicate the coast between Binningup and Cape Bouvard is being eroded in the southern sector and accretion, albeit discontinuous, is more commonly occurring to the

north. This is consistent with the prevailing SW winds, exposure to the SW swell regime and northerly littoral drift.

4. Although the barrier is widest in the northernmost cell (Cell 1 - White Hills Road), erosional features coincide with the rock platform occurring on the beach. Platforms and narrow inshore channels also coincide with the location of scarping or eroded foredunes elsewhere along the barrier.

5. Shoreline movement, indicated by changes to the vegetation line, in the two northern cells (Lake Clifton North and White Hills Road) is a reversal of the overall pattern between Binningup and Cape Bouvard, with the northern flank of salients undergoing accretion and the northern ends of the cells erosion. This is a short to medium term process associated with localised migratory behaviour of sediment around the smaller salients under weak to moderate SW wind conditions, such as periods of prolonged sea breeze activity. It is also associated with higher landform variability than elsewhere along the barrier.

6. The deflation basin, a large erosional feature at the northern end of Cell 3 (Preston Beach) is located in a section with a prograding foredune and small localised blowouts (depositional features). This is apparently due to beach recovery following loss of sediment from the beach system but is consistent with the general erosional character of this part of the coast described in Point 5 above.

7. Stable and/or accreting foredunes occur dominantly in the northern half of the Yalgorup Coast; namely with sections in Cell 1 (White Hills Road) as well as along the southern half of Cell 2 (Lake Clifton North) and continuing into the northern part of Cell 3 (Preston Beach).

5. PROJECTED FUTURE CHANGE

Analysis of the Yalgorup coastal stability has primarily been conducted with reference to historic behaviour, as a means of identifying the processes active along this section of coast. However, it is relevant to recognise that the coastal climate is subject to considerable variability, both due to natural causes and anthropogenic factors, with the latter most strongly linked to those caused by increased Greenhouse gas emissions (IPCC 2007; CSIRO 2007). Both natural and anthropogenic climate variations are subject to uncertainty, with increasing significance when considered over longer time scales. Consequently, coastal management within the region should be undertaken within a framework that recognises this uncertainty.

Potential variations of coastal parameters due to Greenhouse-gas induced climate change have been examined through numerical modelling using a range of possible emission scenarios (IPCC 2007; CSIRO 2007). From the 1980s and 1990s, modelling outputs were mainly focused upon ocean-atmosphere interactions, reflecting changes in temperature and water balance at a global scale. More recently, effort has been made to “downscale” the modelling to a level that provides projection of climate parameters with sufficient resolution to undertake regional climate change assessments.

The best researched and documented components of projected change are temperature and sea level rise, associated with global warming, which are possibly the coastal parameters most amenable to downscaling. Sea level rise estimates fall in the range of 0.3-0.9 m over the next 100 years, with a smaller change of 0.1-0.4 m over the next 50 years (IPCC 2007; CSIRO 2007; Department of Transport 2009b). The well-espoused projected effect of a sea level rise is to cause a landward movement of the shore profile (van Rijn 1996). However, for the Yalgorup coast, such a movement is expected to cause increased exposure and influence of the underlying lithified basement, with the potential to locally retard alongshore sediment transport. Due to the general northerly transport regime, effects of such lagging would likely result in enhanced erosion for the northern part of the Binningup to Cape Bouvard coastal compartment and exacerbate the existing trends for the southern sector.

Preliminary estimates of the wind climate are consistent with a southwards latitudinal shift of the weather bands, with a mild weakening of median winter winds and a slight strengthening of summer median winds (CSIRO 2007). These changes are small (<5%), and the range of uncertainty associated with the modelling is apparently larger than the trend. Projected changes to the southwest region wave climate have not presently been downscaled from global climate models (Hemer *et al*. 2008). Interpretation of the existing wave climate and projected change to wind fields suggests that there would be a general decline of background swell, with a slight increase to summer winds. The effect on alongshore sediment transport is uncertain.

Analysis of variability and secular trends of historic coastal data for south-west Western Australia has been undertaken for a range of coastal parameters, including:

- Synoptic systems (Karelsky 1961; Steedman & Craig 1983; Trenberth 1991)
- Wind observations (Steedman & Associates 1982; Panizza 1983; Damara WA 2003; Oceanica Pty Ltd 2005, 2008; Nicholls *et al*. 2007)
- Wave conditions (Riedel & Trajer 1978; Lemm 1996; CZM & Damara WA 2008; Department of Transport 2009a); and
- Water levels (Wallace 1996; National Tidal Facility 2004; Feng *et al*. 2004; Eliot & Pattiaratchi 2006; Pattiaratchi & Eliot 2008).

Typically, these analyses have shown considerable variability at seasonal and sub-decadal time scales. The most widely recognised variations are those linked to El Nino-La Nina climate oscillations. However, in most cases, comparatively short records (< 30 years) or changes of instrumentation limit the capacity to identify inter-decadal fluctuations or to describe secular trends.

Coastal climate variation over the historic period is generally larger than the predicted anthropogenic forcing over the next 30 years (Eliot & Pattiaratchi 2006; CZM & Damara WA 2008). Consequently, the natural variability may either mask or exacerbate the effects of climate-change induced trends, depending upon the active phase. Due to the apparent sensitivity of the Yalgorup coast to different coastal parameters, interpretation of the effects of climate variability, including anthropogenic change, should consider a range of possible scenarios, with variation of winds, wave conditions and water levels.

6. ACKNOWLEDGEMENTS

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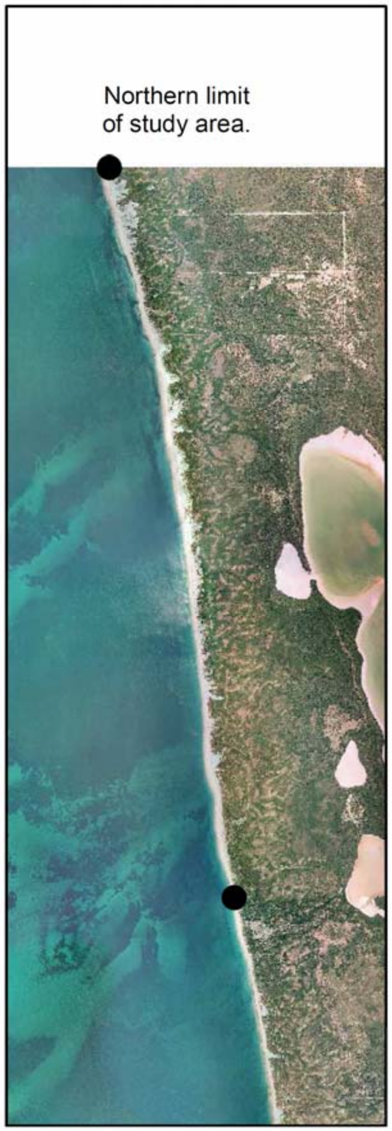
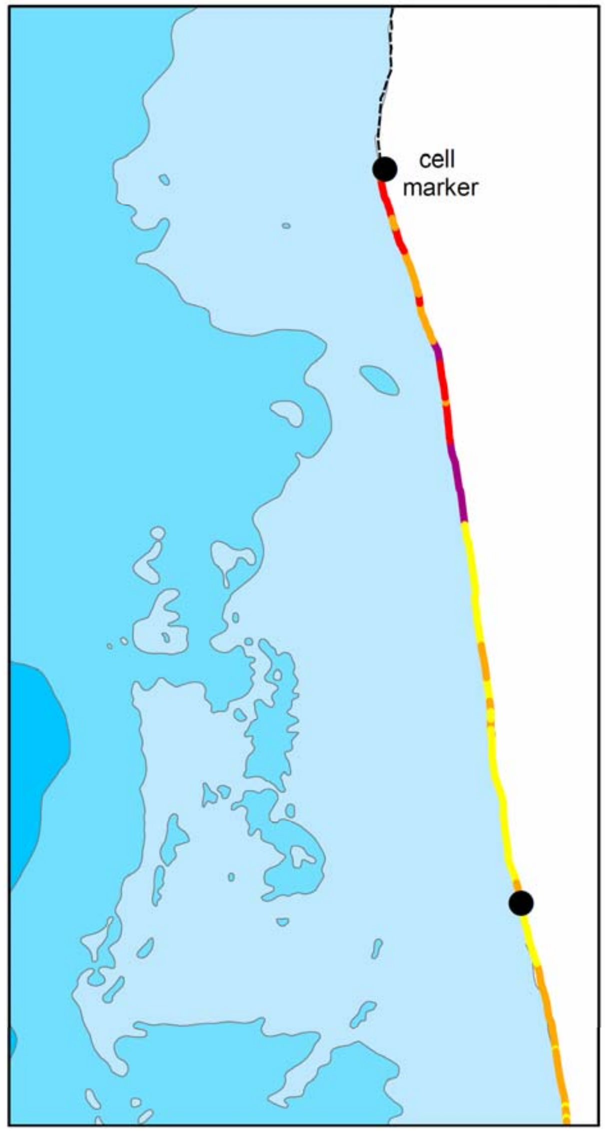
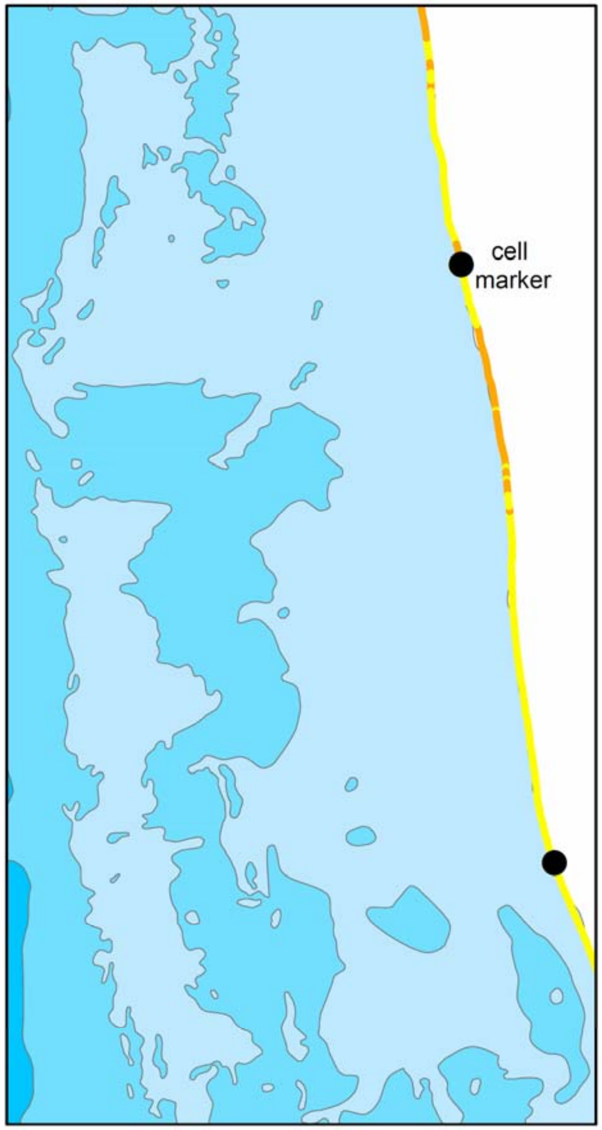
APPENDIX 1 LANDFORMS AND COASTAL CHANGE

A Geological Framework & Bathymetry

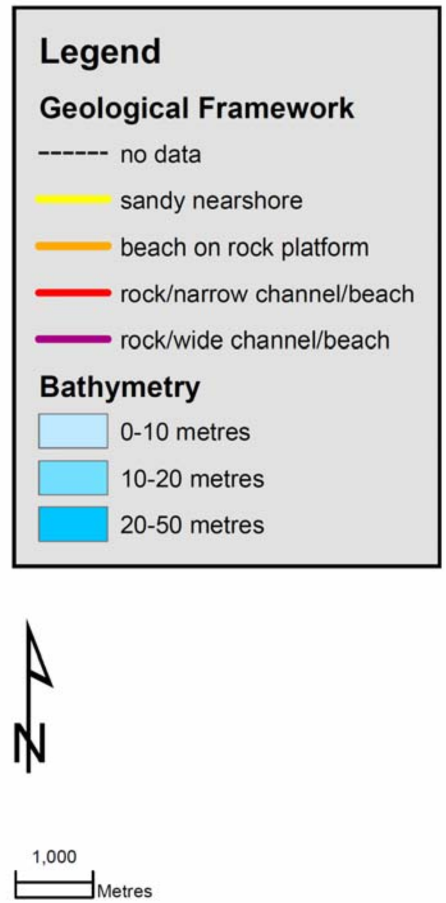
Cell 1: Geological Framework and Bathymetry.

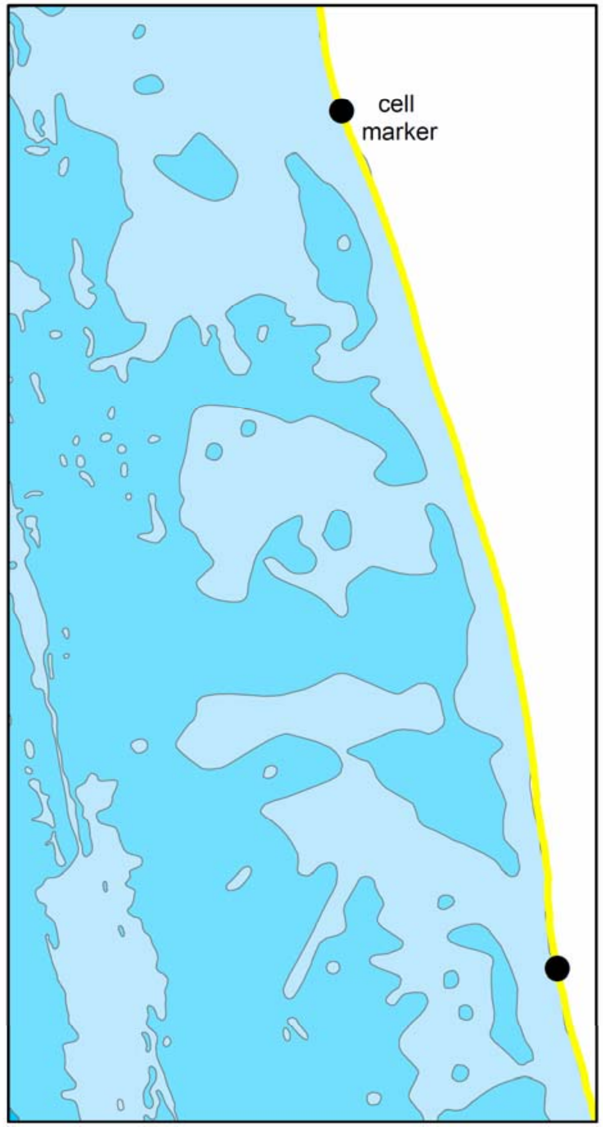






Cell 2: Geological Framework and Bathymetry.





Cell 3: Geological Framework and Bathymetry.

Legend

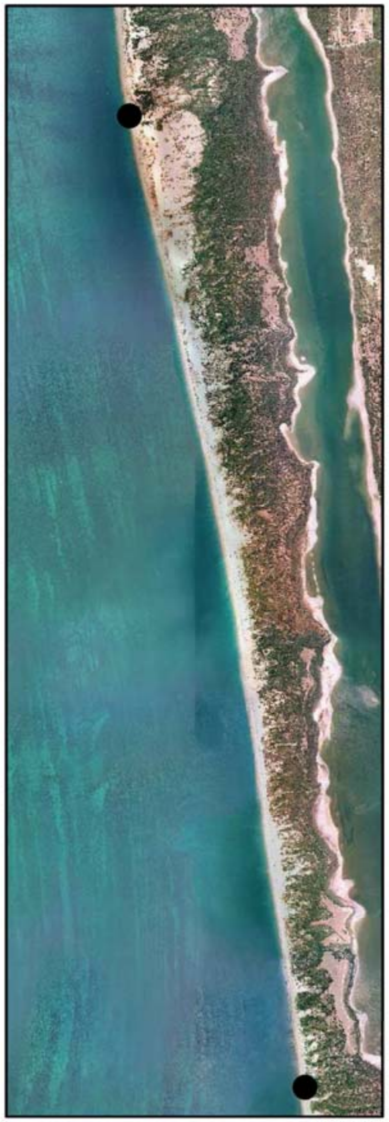
Geological Framework

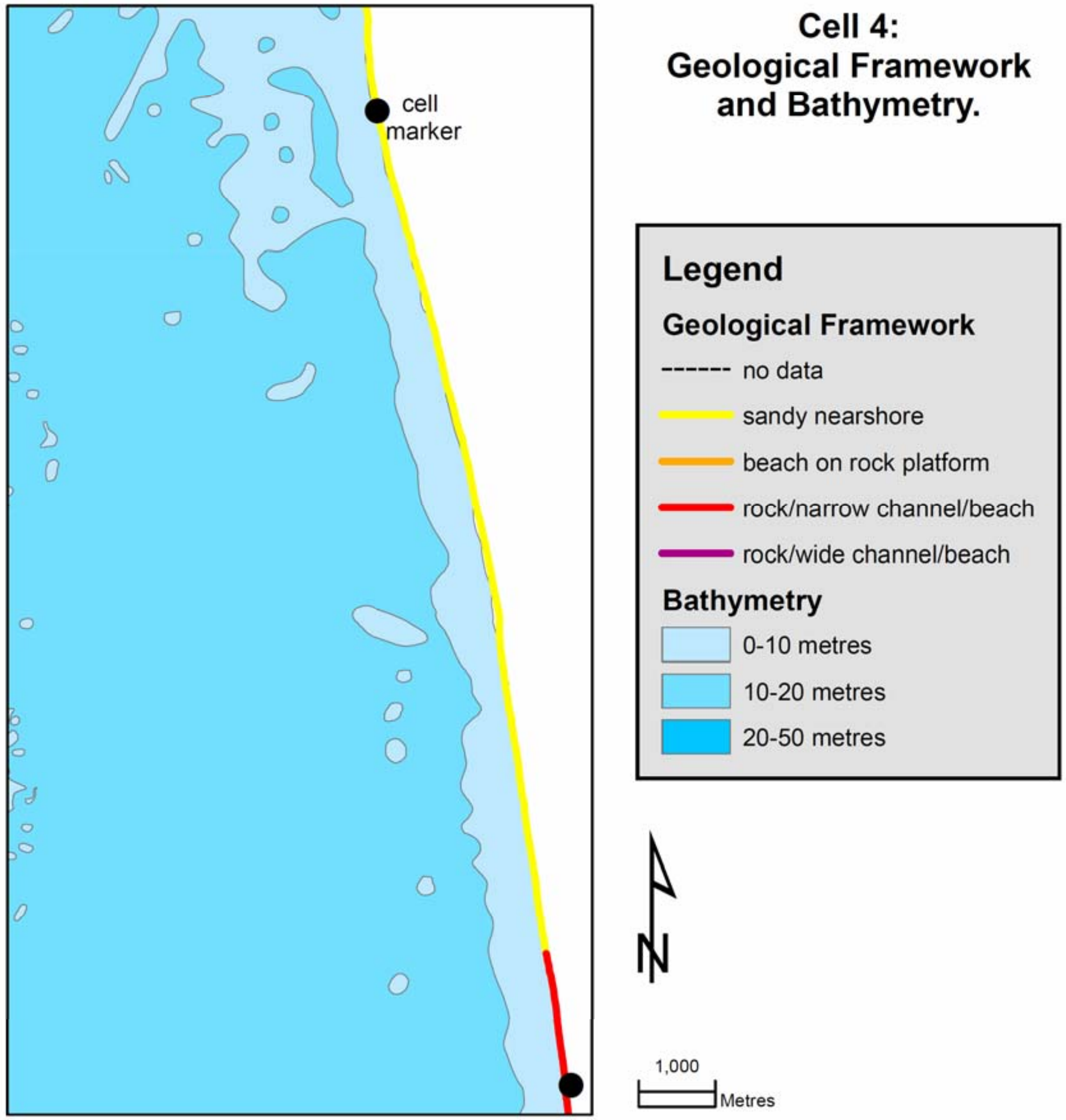
- no data
- sandy nearshore
- beach on rock platform
- rock/narrow channel/beach
- rock/wide channel/beach

Bathymetry

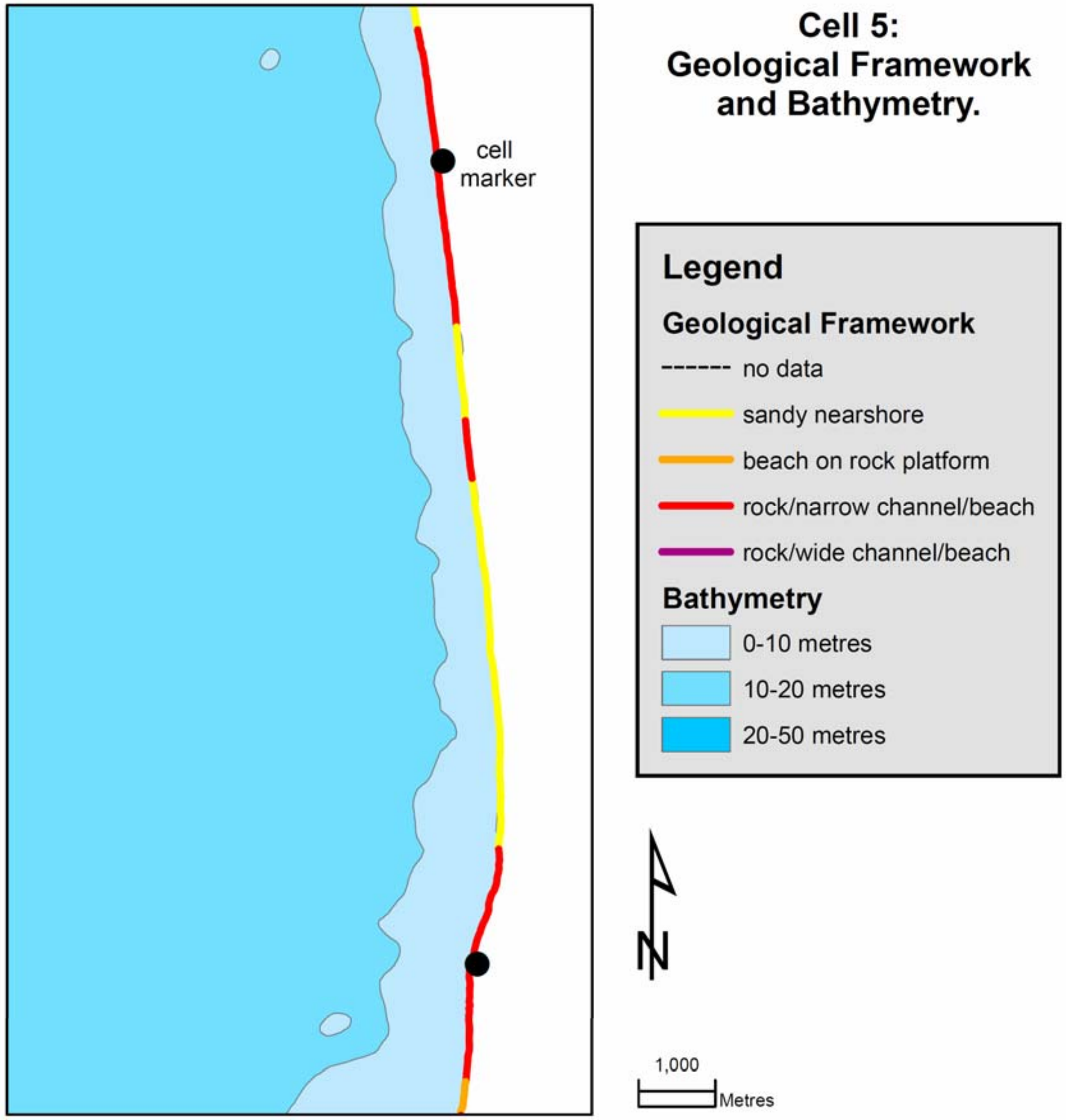
- 0-10 metres
- 10-20 metres
- 20-50 metres

Cell 4: Geological Framework and Bathymetry.





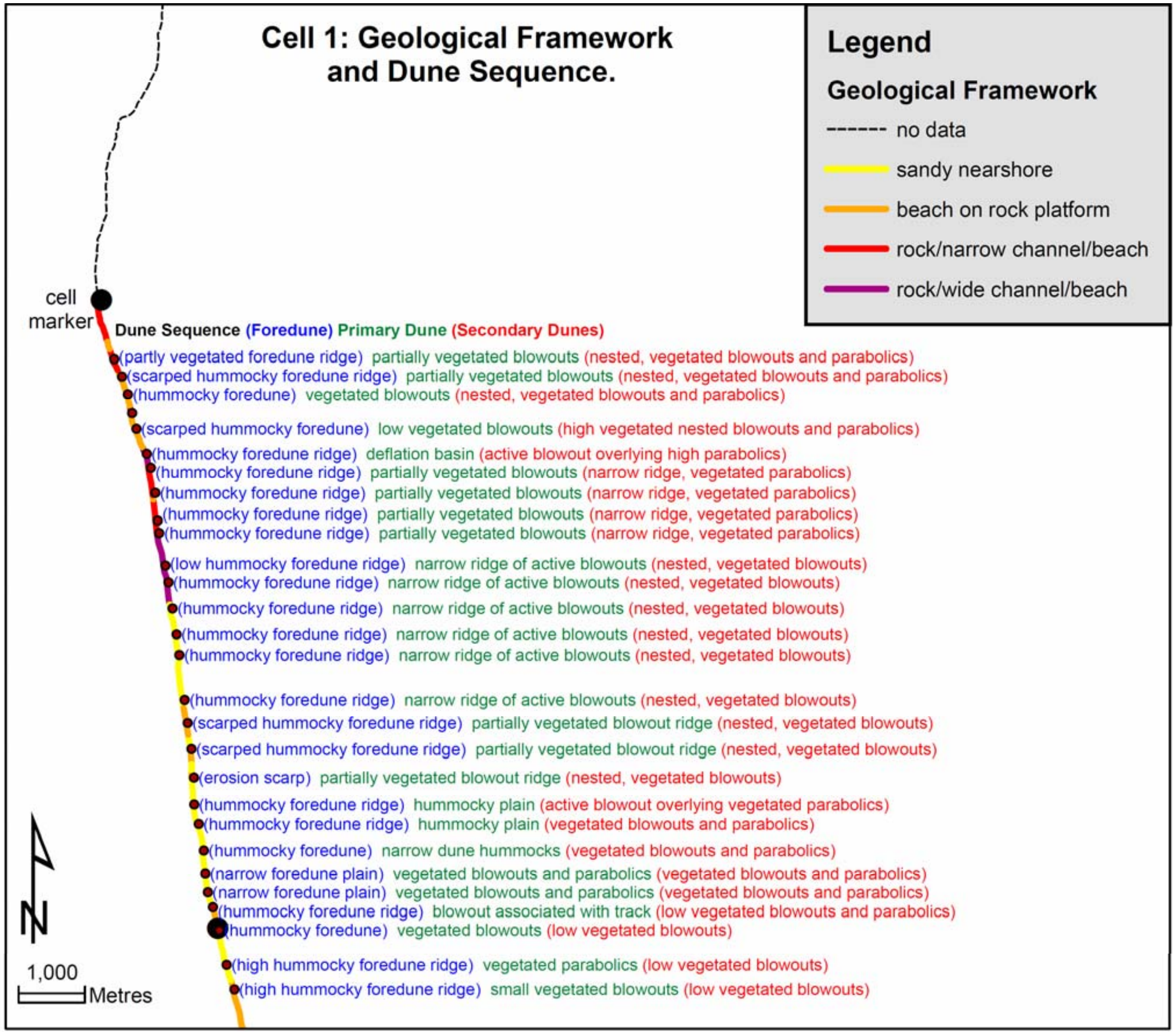
Cell 5: Geological Framework and Bathymetry.

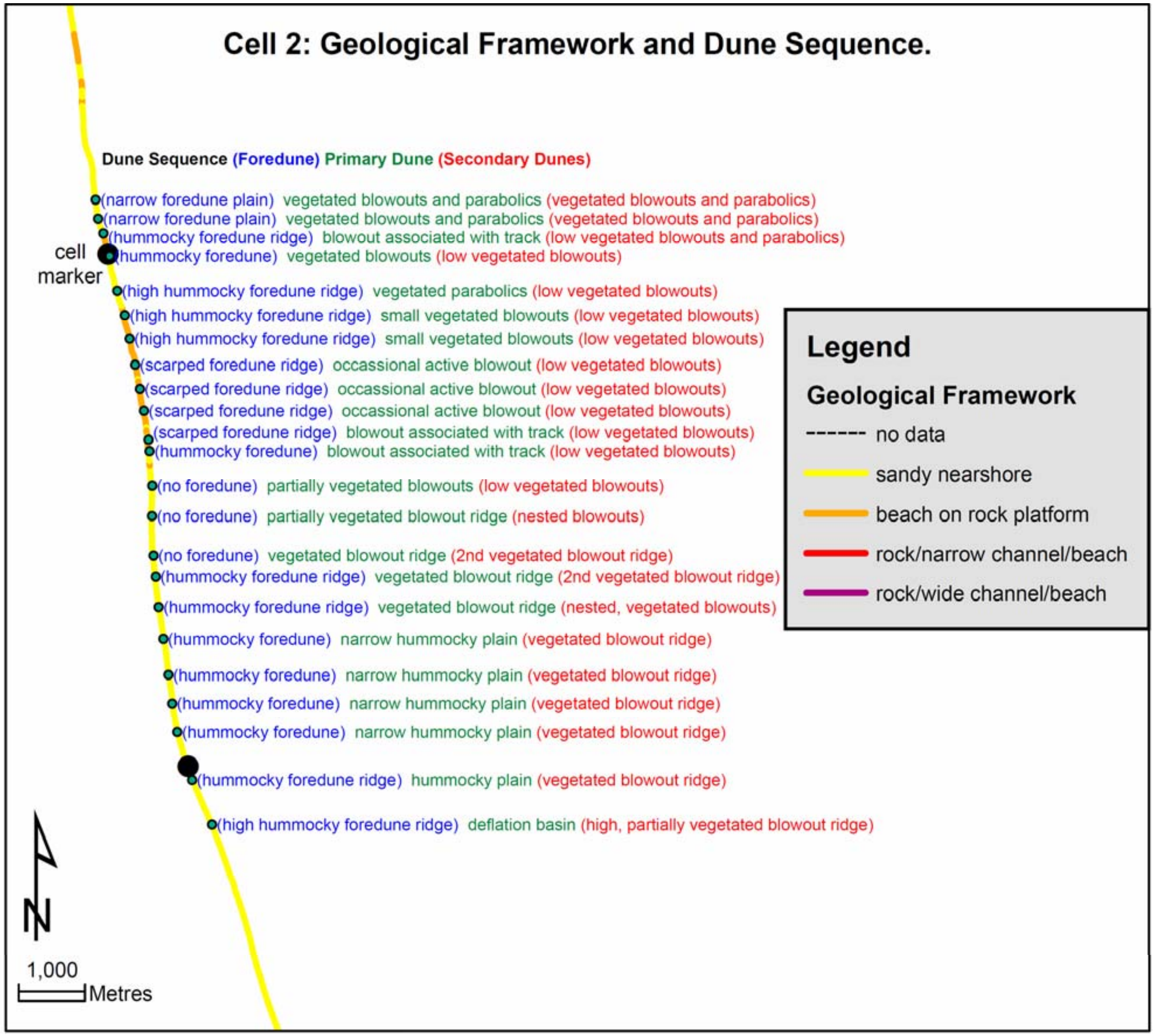


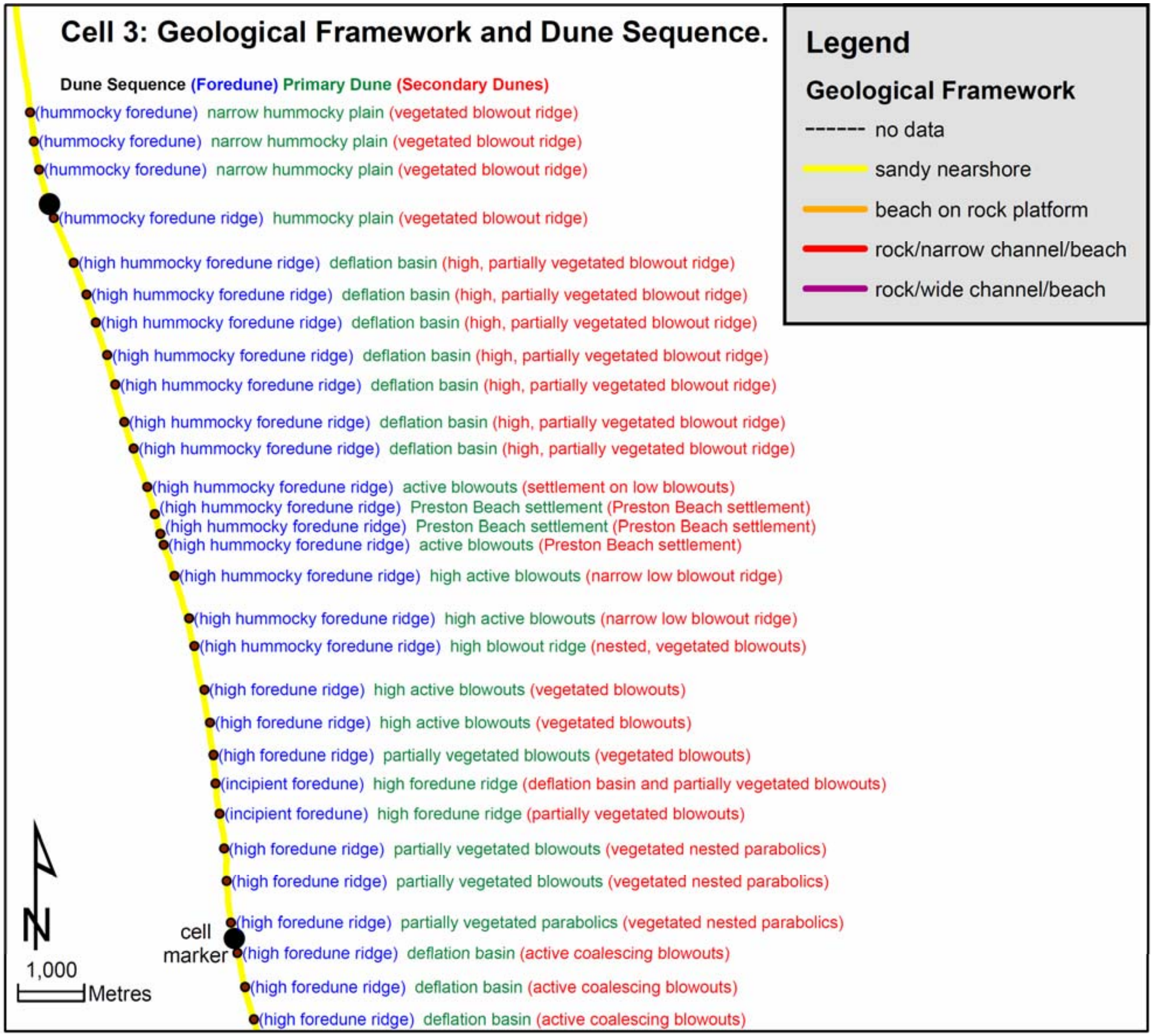
APPENDIX 1 LANDFORMS AND COASTAL CHANGE

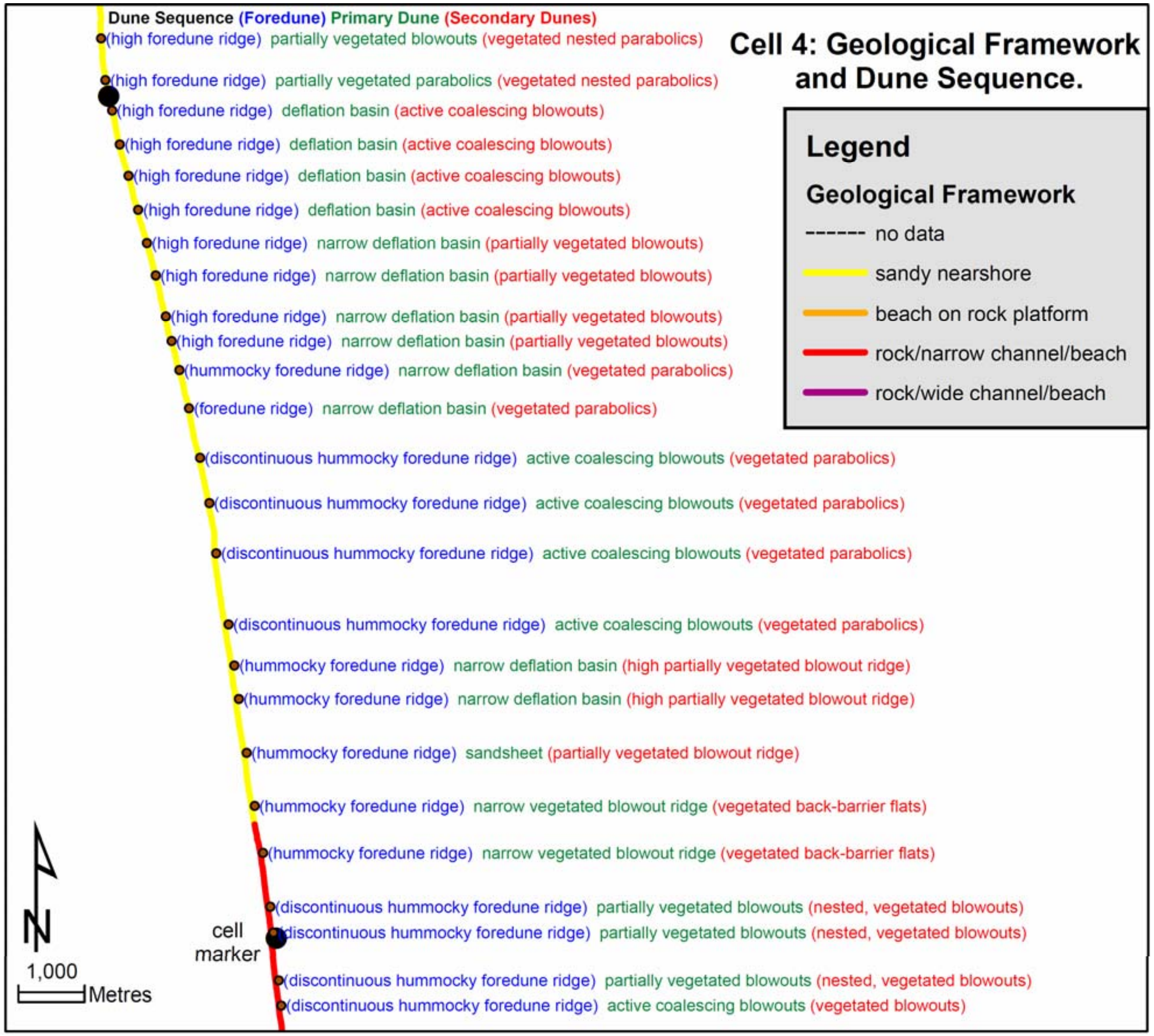
B Geological Framework & Dune Sequence

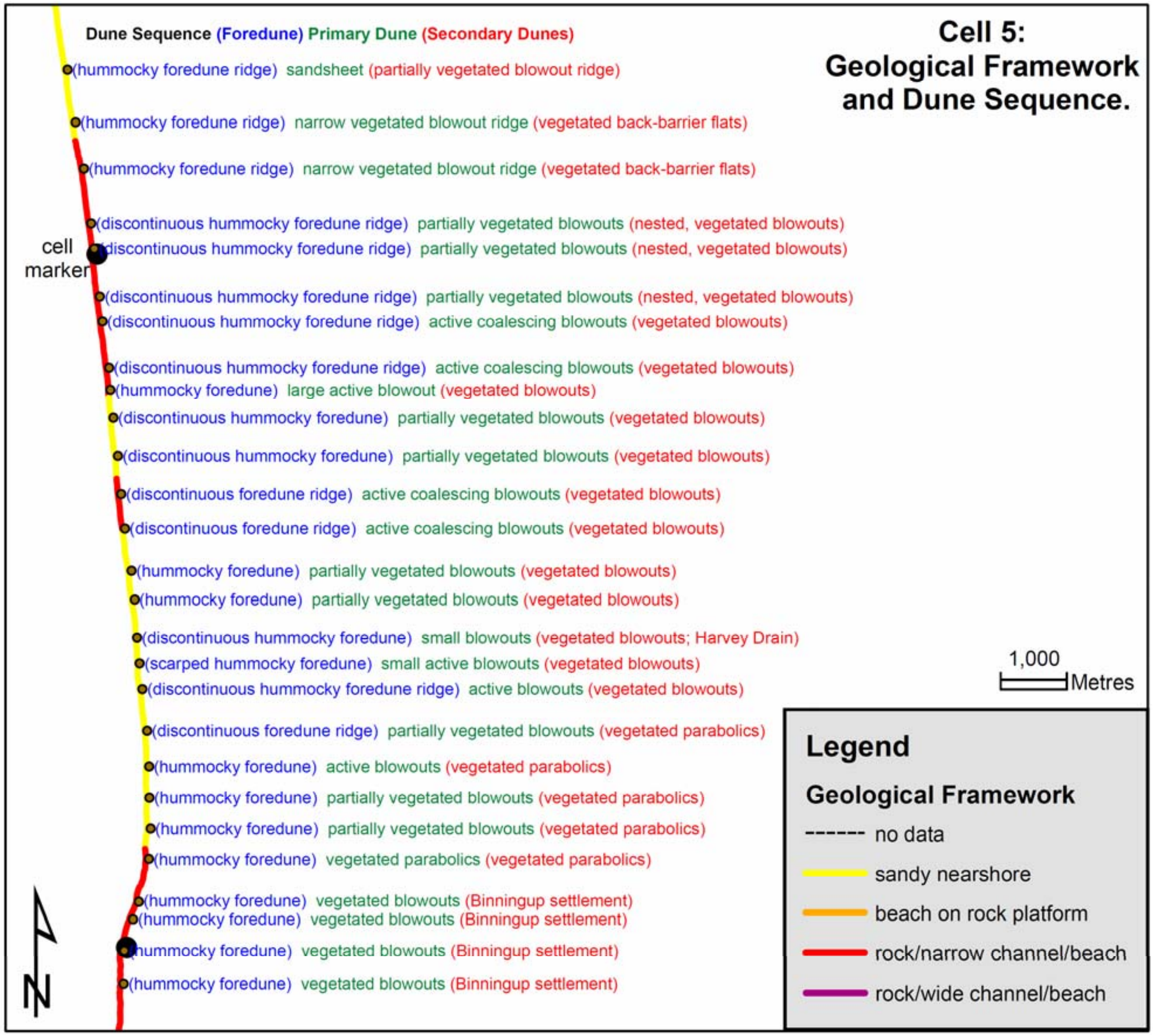

Northern limit
of study area.


Cell 1: Geological Framework
and Dune Sequence.
Legend
Geological Framework
no data
sandy nearshore
beach on rock platform
rock/narrow channel/beach
rock/wide channel/beach
cell
marker
Dune Sequence (Foredune) Primary Dune (Secondary Dunes)
(partly vegetated foredune ridge) partially vegetated blowouts (nested, vegetated blowouts and parabolics)
(scarped hummocky foredune ridge) partially vegetated blowouts (nested, vegetated blowouts and parabolics)
(hummocky foredune) vegetated blowouts (nested, vegetated blowouts and parabolics)
(scarped hummocky foredune) low vegetated blowouts (high vegetated nested blowouts and parabolics)
(hummocky foredune ridge) deflation basin (active blowout overlying high parabolics)
(hummocky foredune ridge) partially vegetated blowouts (narrow ridge, vegetated parabolics)
(hummocky foredune ridge) partially vegetated blowouts (narrow ridge, vegetated parabolics)
(hummocky foredune ridge) partially vegetated blowouts (narrow ridge, vegetated parabolics)
(hummocky foredune ridge) partially vegetated blowouts (narrow ridge, vegetated parabolics)
(low hummocky foredune ridge) narrow ridge of active blowouts (nested, vegetated blowouts)
(hummocky foredune ridge) narrow ridge of active blowouts (nested, vegetated blowouts)
(hummocky foredune ridge) narrow ridge of active blowouts (nested, vegetated blowouts)
(hummocky foredune ridge) narrow ridge of active blowouts (nested, vegetated blowouts)
(hummocky foredune ridge) narrow ridge of active blowouts (nested, vegetated blowouts)
(hummocky foredune ridge) narrow ridge of active blowouts (nested, vegetated blowouts)
(scarped hummocky foredune ridge) partially vegetated blowout ridge (nested, vegetated blowouts)
(scarped hummocky foredune ridge) partially vegetated blowout ridge (nested, vegetated blowouts)
(erosion scarp) partially vegetated blowout ridge (nested, vegetated blowouts)
(hummocky foredune ridge) hummocky plain (active blowout overlying vegetated parabolics)
(hummocky foredune ridge) hummocky plain (vegetated blowouts and parabolics)
(hummocky foredune) narrow dune hummocks (vegetated blowouts and parabolics)
(narrow foredune plain) vegetated blowouts and parabolics (vegetated blowouts and parabolics)
(narrow foredune plain) vegetated blowouts and parabolics (vegetated blowouts and parabolics)
(hummocky foredune ridge) blowout associated with track (low vegetated blowouts and parabolics)
(hummocky foredune) vegetated blowouts (low vegetated blowouts)
(high hummocky foredune ridge) vegetated parabolics (low vegetated blowouts)
(high hummocky foredune ridge) small vegetated blowouts (low vegetated blowouts)
N
1,000
Metres


Cell 2: Geological Framework and Dune Sequence.
Dune Sequence (Foredune) Primary Dune (Secondary Dunes)
(narrow foredune plain) vegetated blowouts and parabolics (vegetated blowouts and parabolics)
(narrow foredune plain) vegetated blowouts and parabolics (vegetated blowouts and parabolics)
(hummocky foredune ridge) blowout associated with track (low vegetated blowouts and parabolics)
(hummocky foredune) vegetated blowouts (low vegetated blowouts)
cell marker
(high hummocky foredune ridge) vegetated parabolics (low vegetated blowouts)
(high hummocky foredune ridge) small vegetated blowouts (low vegetated blowouts)
(high hummocky foredune ridge) small vegetated blowouts (low vegetated blowouts)
(scarped foredune ridge) occassional active blowout (low vegetated blowouts)
(scarped foredune ridge) occassional active blowout (low vegetated blowouts)
(scarped foredune ridge) occassional active blowout (low vegetated blowouts)
(scarped foredune ridge) blowout associated with track (low vegetated blowouts)
(hummocky foredune) blowout associated with track (low vegetated blowouts)
(no foredune) partially vegetated blowouts (low vegetated blowouts)
(no foredune) partially vegetated blowout ridge (nested blowouts)
(no foredune) vegetated blowout ridge (2nd vegetated blowout ridge)
(hummocky foredune ridge) vegetated blowout ridge (2nd vegetated blowout ridge)
(hummocky foredune ridge) vegetated blowout ridge (nested, vegetated blowouts)
(hummocky foredune) narrow hummocky plain (vegetated blowout ridge)
(hummocky foredune) narrow hummocky plain (vegetated blowout ridge)
(hummocky foredune) narrow hummocky plain (vegetated blowout ridge)
(hummocky foredune) narrow hummocky plain (vegetated blowout ridge)
(hummocky foredune ridge) hummocky plain (vegetated blowout ridge)
(high hummocky foredune ridge) deflation basin (high, partially vegetated blowout ridge)
Legend
Geological Framework
------ no data
sandy nearshore
beach on rock platform
rock/narrow channel/beach
rock/wide channel/beach
N
1,000
Metres

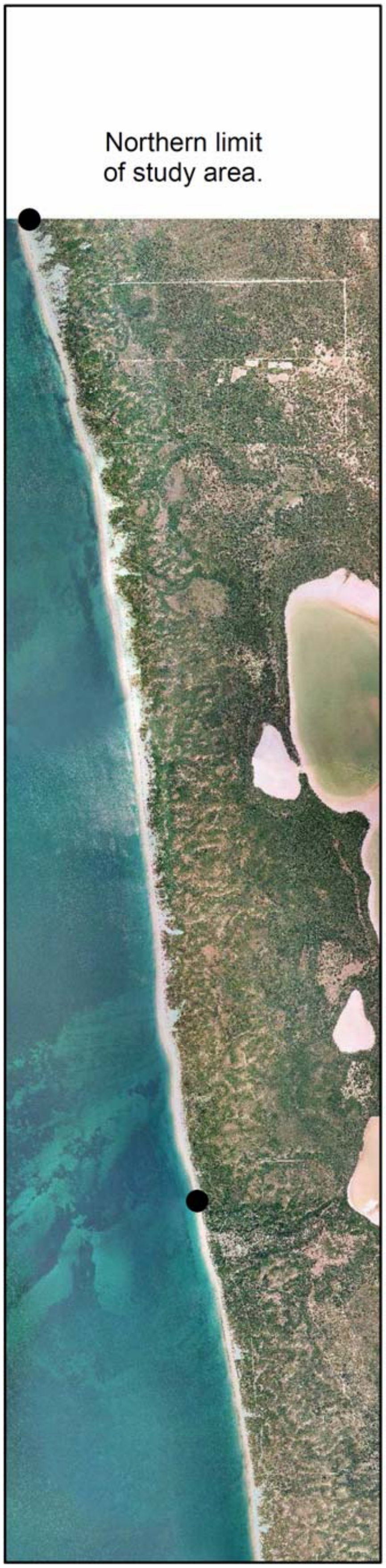

Cell 3: Geological Framework and Dune Sequence.
Dune Sequence (Foredune) Primary Dune (Secondary Dunes)
(hummocky foredune) narrow hummocky plain (vegetated blowout ridge)
(hummocky foredune) narrow hummocky plain (vegetated blowout ridge)
(hummocky foredune) narrow hummocky plain (vegetated blowout ridge)
(hummocky foredune ridge) hummocky plain (vegetated blowout ridge)
(high hummocky foredune ridge) deflation basin (high, partially vegetated blowout ridge)
(high hummocky foredune ridge) deflation basin (high, partially vegetated blowout ridge)
(high hummocky foredune ridge) deflation basin (high, partially vegetated blowout ridge)
(high hummocky foredune ridge) deflation basin (high, partially vegetated blowout ridge)
(high hummocky foredune ridge) deflation basin (high, partially vegetated blowout ridge)
(high hummocky foredune ridge) deflation basin (high, partially vegetated blowout ridge)
(high hummocky foredune ridge) deflation basin (high, partially vegetated blowout ridge)
(high hummocky foredune ridge) active blowouts (settlement on low blowouts)
(high hummocky foredune ridge) Preston Beach settlement (Preston Beach settlement)
(high hummocky foredune ridge) Preston Beach settlement (Preston Beach settlement)
(high hummocky foredune ridge) active blowouts (Preston Beach settlement)
(high hummocky foredune ridge) high active blowouts (narrow low blowout ridge)
(high hummocky foredune ridge) high active blowouts (narrow low blowout ridge)
(high hummocky foredune ridge) high blowout ridge (nested, vegetated blowouts)
(high foredune ridge) high active blowouts (vegetated blowouts)
(high foredune ridge) high active blowouts (vegetated blowouts)
(high foredune ridge) partially vegetated blowouts (vegetated blowouts)
(incipient foredune) high foredune ridge (deflation basin and partially vegetated blowouts)
(incipient foredune) high foredune ridge (partially vegetated blowouts)
(high foredune ridge) partially vegetated blowouts (vegetated nested parabolics)
(high foredune ridge) partially vegetated blowouts (vegetated nested parabolics)
(high foredune ridge) partially vegetated parabolics (vegetated nested parabolics)
(high foredune ridge) deflation basin (active coalescing blowouts)
(high foredune ridge) deflation basin (active coalescing blowouts)
(high foredune ridge) deflation basin (active coalescing blowouts)
cell marker
N
1,000 Metres
Legend
Geological Framework
no data
sandy nearshore
beach on rock platform
rock/narrow channel/beach
rock/wide channel/beach

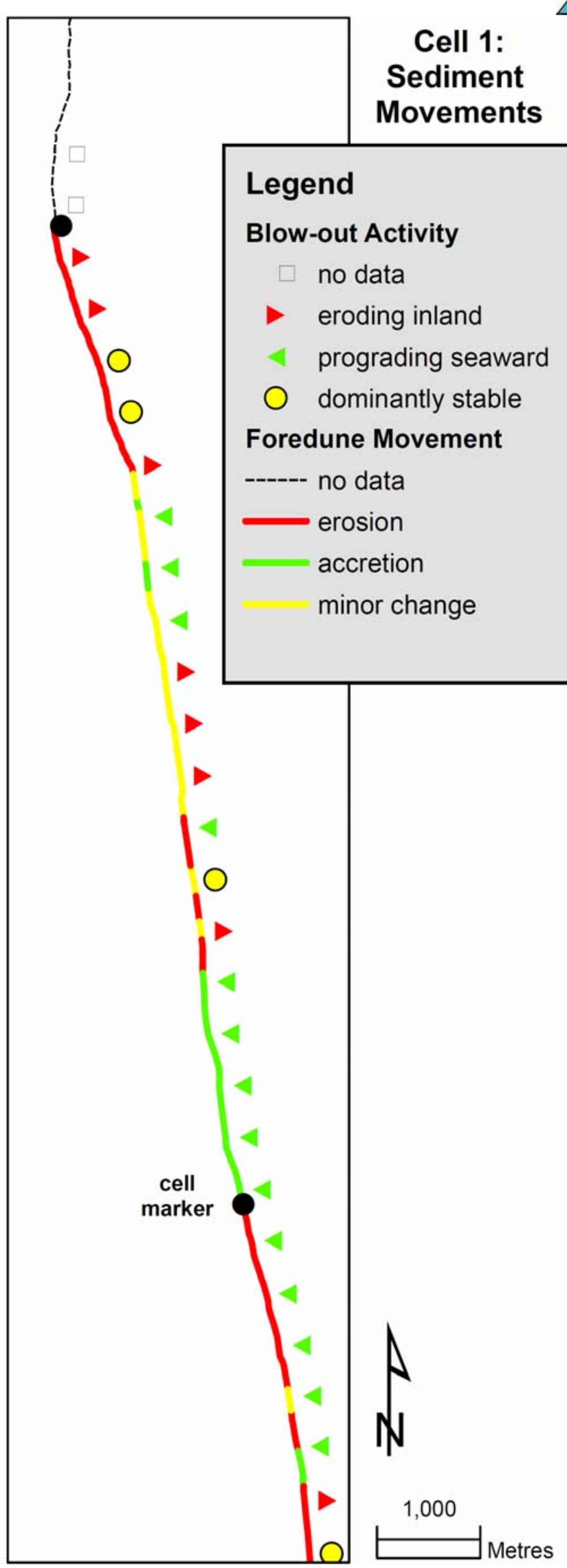

Cell 4: Geological Framework and Dune Sequence.
Legend
Geological Framework
------ no data
sandy nearshore
beach on rock platform
rock/narrow channel/beach
rock/wide channel/beach
Dune Sequence (Foredune) Primary Dune (Secondary Dunes)
(high foredune ridge) partially vegetated blowouts (vegetated nested parabolics)
(high foredune ridge) partially vegetated parabolics (vegetated nested parabolics)
(high foredune ridge) deflation basin (active coalescing blowouts)
(high foredune ridge) deflation basin (active coalescing blowouts)
(high foredune ridge) deflation basin (active coalescing blowouts)
(high foredune ridge) deflation basin (active coalescing blowouts)
(high foredune ridge) narrow deflation basin (partially vegetated blowouts)
(high foredune ridge) narrow deflation basin (partially vegetated blowouts)
(high foredune ridge) narrow deflation basin (partially vegetated blowouts)
(high foredune ridge) narrow deflation basin (partially vegetated blowouts)
(hummocky foredune ridge) narrow deflation basin (vegetated parabolics)
(foredune ridge) narrow deflation basin (vegetated parabolics)
(discontinuous hummocky foredune ridge) active coalescing blowouts (vegetated parabolics)
(discontinuous hummocky foredune ridge) active coalescing blowouts (vegetated parabolics)
(discontinuous hummocky foredune ridge) active coalescing blowouts (vegetated parabolics)
(discontinuous hummocky foredune ridge) active coalescing blowouts (vegetated parabolics)
(hummocky foredune ridge) narrow deflation basin (high partially vegetated blowout ridge)
(hummocky foredune ridge) narrow deflation basin (high partially vegetated blowout ridge)
(hummocky foredune ridge) sandsheet (partially vegetated blowout ridge)
(hummocky foredune ridge) narrow vegetated blowout ridge (vegetated back-barrier flats)
(hummocky foredune ridge) narrow vegetated blowout ridge (vegetated back-barrier flats)
(discontinuous hummocky foredune ridge) partially vegetated blowouts (nested, vegetated blowouts)
(discontinuous hummocky foredune ridge) partially vegetated blowouts (nested, vegetated blowouts)
(discontinuous hummocky foredune ridge) partially vegetated blowouts (nested, vegetated blowouts)
(discontinuous hummocky foredune ridge) active coalescing blowouts (vegetated blowouts)
N
1,000
Metres
cell
marker

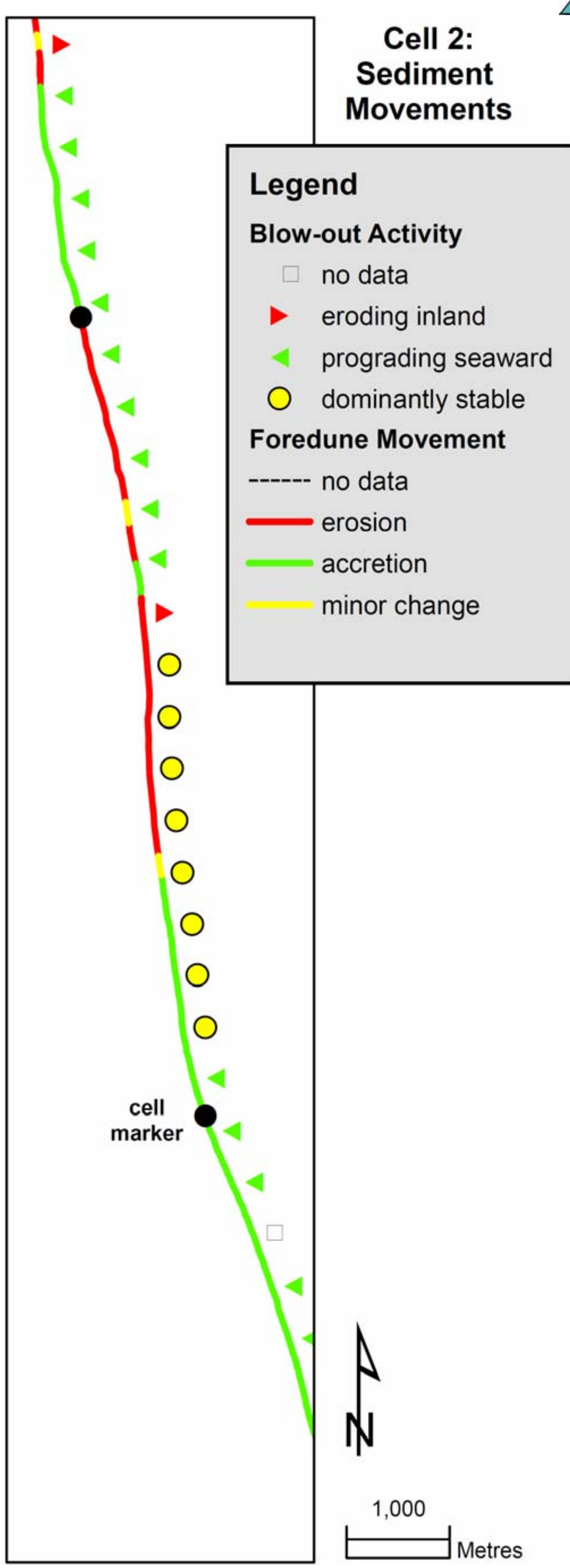

Cell 5:
Geological Framework and Dune Sequence.
Dune Sequence (Foredune) Primary Dune (Secondary Dunes)
(hummocky foredune ridge) sandsheet (partially vegetated blowout ridge)
(hummocky foredune ridge) narrow vegetated blowout ridge (vegetated back-barrier flats)
(hummocky foredune ridge) narrow vegetated blowout ridge (vegetated back-barrier flats)
(discontinuous hummocky foredune ridge) partially vegetated blowouts (nested, vegetated blowouts)
(discontinuous hummocky foredune ridge) partially vegetated blowouts (nested, vegetated blowouts)
cell marker
(discontinuous hummocky foredune ridge) partially vegetated blowouts (nested, vegetated blowouts)
(discontinuous hummocky foredune ridge) active coalescing blowouts (vegetated blowouts)
(discontinuous hummocky foredune ridge) active coalescing blowouts (vegetated blowouts)
(hummocky foredune) large active blowout (vegetated blowouts)
(discontinuous hummocky foredune) partially vegetated blowouts (vegetated blowouts)
(discontinuous hummocky foredune) partially vegetated blowouts (vegetated blowouts)
(discontinuous foredune ridge) active coalescing blowouts (vegetated blowouts)
(discontinuous foredune ridge) active coalescing blowouts (vegetated blowouts)
(hummocky foredune) partially vegetated blowouts (vegetated blowouts)
(hummocky foredune) partially vegetated blowouts (vegetated blowouts)
(discontinuous hummocky foredune) small blowouts (vegetated blowouts; Harvey Drain)
(scarped hummocky foredune) small active blowouts (vegetated blowouts)
(discontinuous hummocky foredune ridge) active blowouts (vegetated blowouts)
(discontinuous foredune ridge) partially vegetated blowouts (vegetated parabolics)
(hummocky foredune) active blowouts (vegetated parabolics)
(hummocky foredune) partially vegetated blowouts (vegetated parabolics)
(hummocky foredune) partially vegetated blowouts (vegetated parabolics)
(hummocky foredune) vegetated parabolics (vegetated parabolics)
(hummocky foredune) vegetated blowouts (Binningup settlement)
(hummocky foredune) vegetated blowouts (Binningup settlement)
(hummocky foredune) vegetated blowouts (Binningup settlement)
(hummocky foredune) vegetated blowouts (Binningup settlement)
N
1,000
Metres
Legend
Geological Framework
no data
sandy nearshore
beach on rock platform
rock/narrow channel/beach
rock/wide channel/beach

APPENDIX 1 LANDFORMS AND COASTAL CHANGE

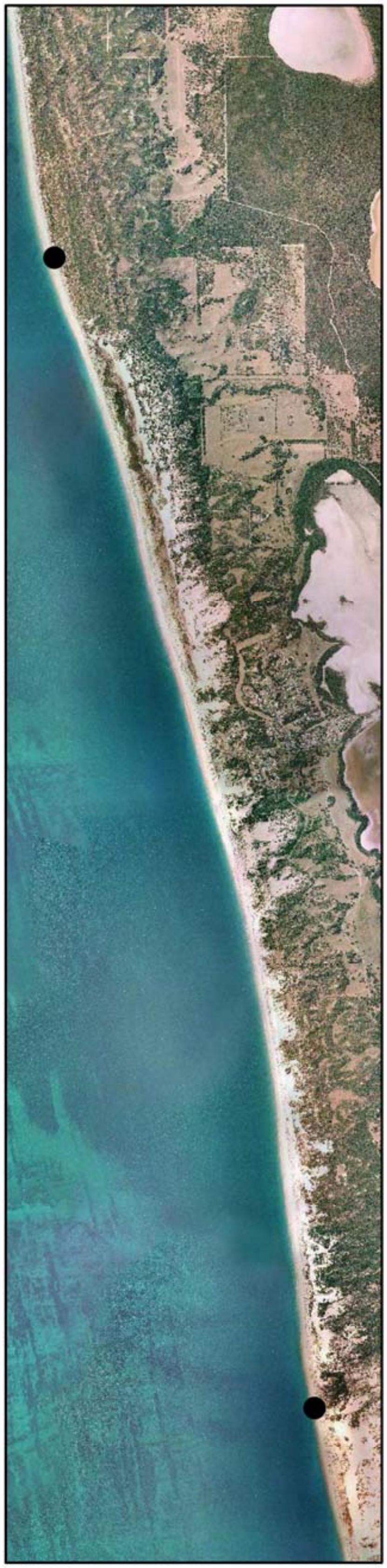
C Blowout Activity & Foredune Movement

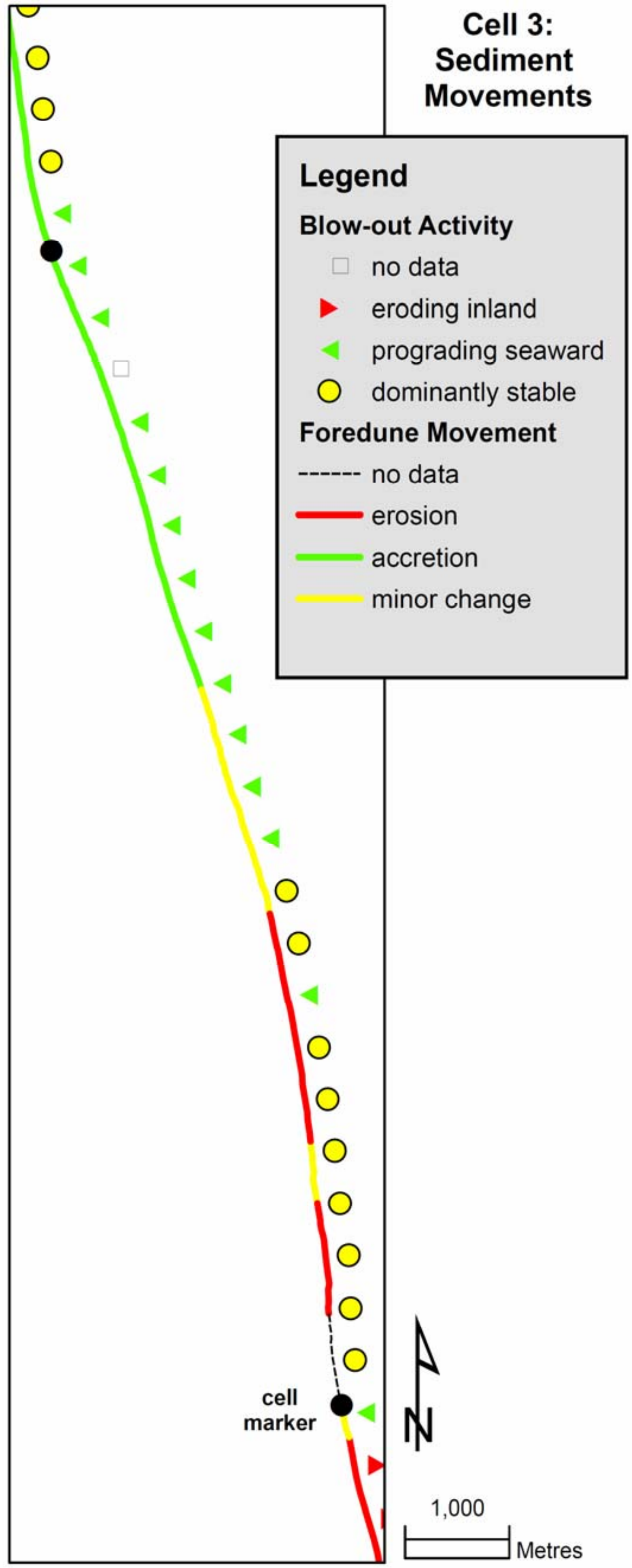

Northern limit
of study area.

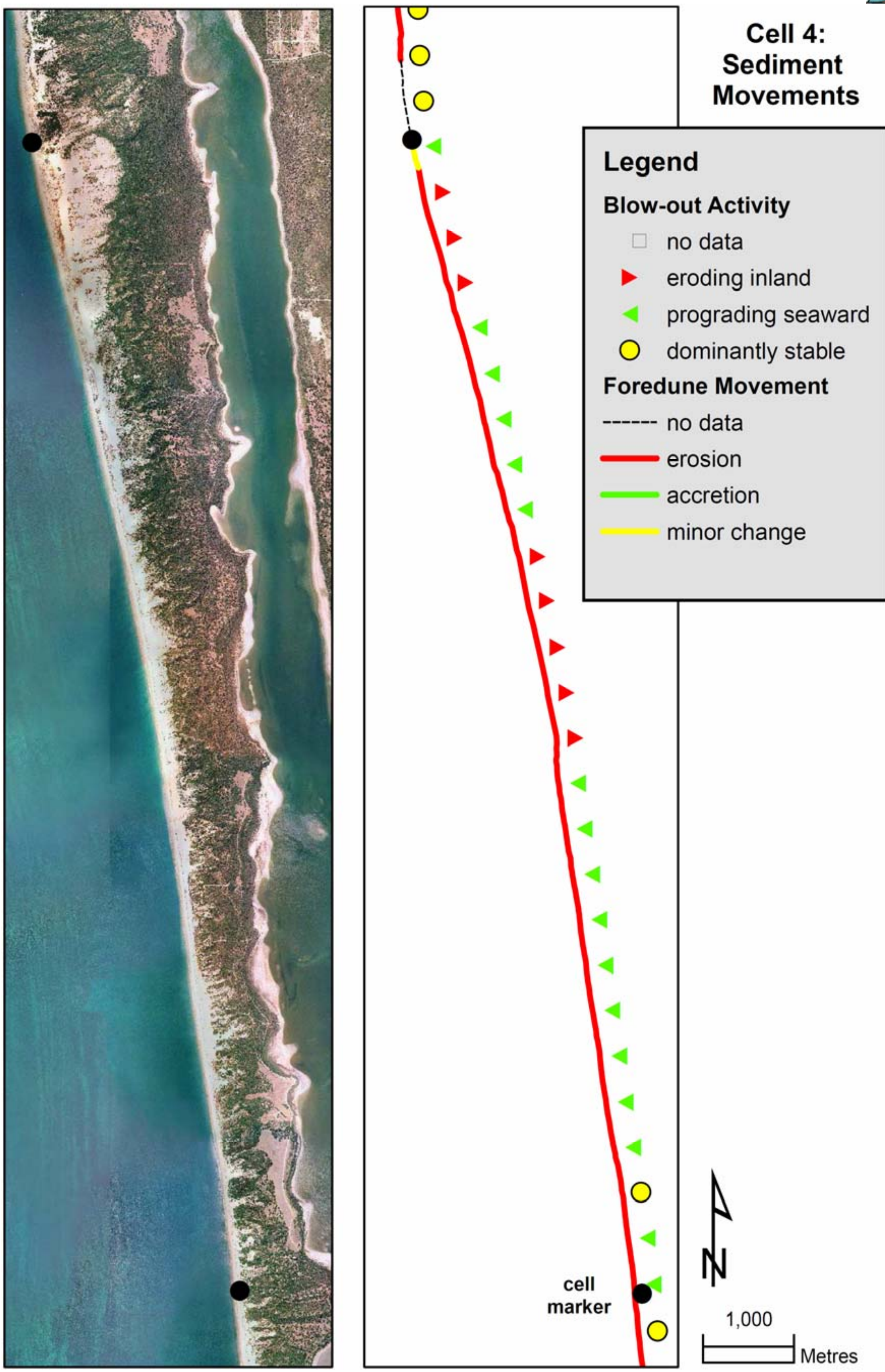

Cell 1:
Sediment
Movements
Legend
Blow-out Activity
no data
eroding inland
prograding seaward
dominantly stable
Foredune Movement
no data
erosion
accretion
minor change
cell
marker
N
1,000
Metres

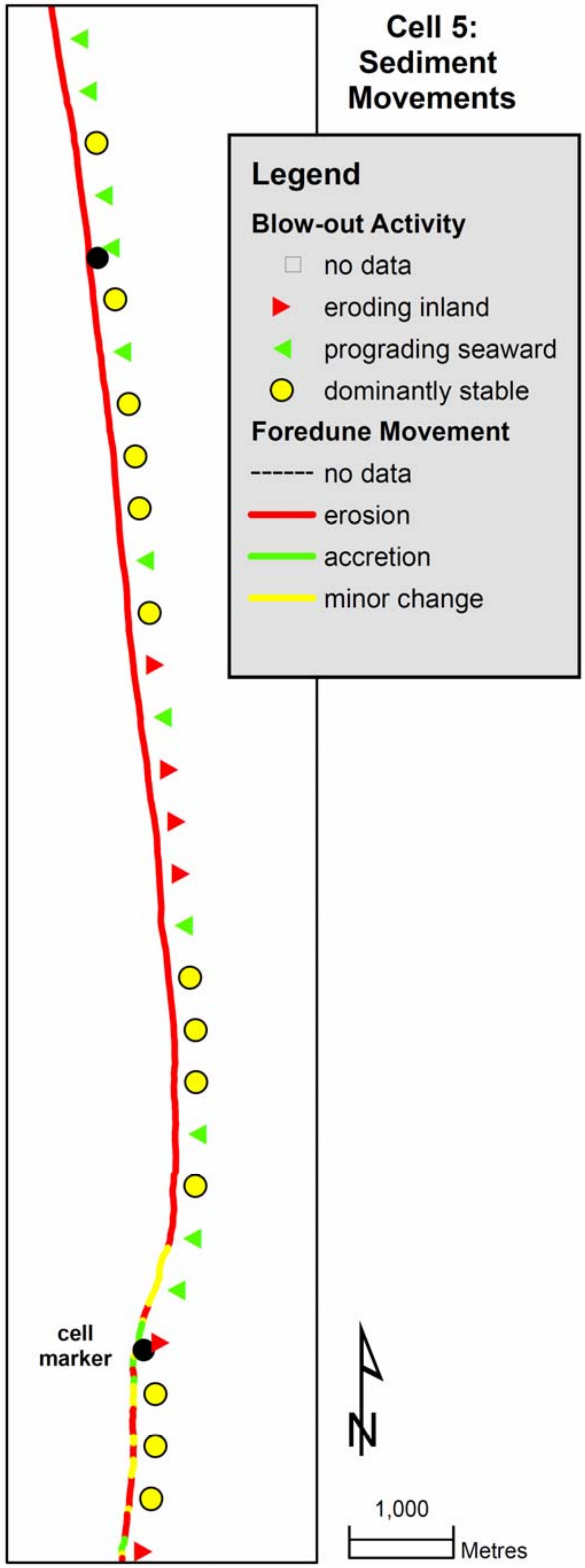

Cell 2:
Sediment
Movements
Legend
Blow-out Activity
no data
eroding inland
prograding seaward
dominantly stable
Foredune Movement
------ no data
erosion
accretion
minor change
cell
marker
N
1,000
Metres

Cell 3: Sediment Movements






Cell 4:
Sediment
Movements
Legend
Blow-out Activity
no data
eroding inland
prograding seaward
dominantly stable
Foredune Movement
no data
erosion
accretion
minor change
cell
marker
1,000
Metres


Cell 5:
Sediment
Movements
Legend
Blow-out Activity
no data
eroding inland
prograding seaward
dominantly stable
Foredune Movement
------ no data
erosion
accretion
minor change
cell
marker
N
1,000
Metres