TECHNICAL REPORT

The Coast of the Shires of Coorow to Northampton, Mid West, Western Australia:

Geology, Geomorphology and Vulnerability

December 2012

GOVERNMENT OF WESTERN AUSTRALIA
Department of Planning
Department of Transport

The Department of Planning engaged Damara WA Pty Ltd to prepare this report as a background technical guidance document only. Damara conducted this project in conjunction with the Geological Survey of Western Australia.

Damara WA Pty Ltd
Email: office@damarawa.com
Tel: (08) 9445 1986

Geological Survey of Western Australia
Department of Mines and Petroleum
Tel: (08) 9222 3333

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Cover Photograph
View northeast over the southern end of Port Gregory and across a 1 km wide barrier comprised nested parabolic dunes to the Hutt Lagoon, Beta carotene ponds, the delta of the Hutt River and Lytton Station. A tombolo and cuspate foreland are apparent at the shore. (Photograph: I. Eliot)

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website: www.planning.wa.gov.au
email: corporate@planning.wa.gov.au

tel: 08 655 19000
fax: 08 655 19001
National Relay Service: 13 36 77
infoline: 1800 626 477

EXECUTIVE SUMMARY

Approach

The Mid-West is a transitional region physically and climatologically. It spans the shallow reefs and inshore lagoons that are common south of Dongara and the deeper shoreface north of Glenfield. Additionally, streams and rivers are increasingly common to the north of the Study Area, with the Irwin River at Dongara, Chapman River at Geraldton, and several small streams between there and the Murchison River at Kalbarri. Despite the presence of the streams the northern sector of the Study Area is apparently sediment deficient. The largest unconsolidated sedimentary landforms – cuspate forelands and high barriers - are predominantly located along the southern shores. Conversely, extensive erosional forms, such as large cliffs and lagoons landward of exposed platforms are more prevalent in the northern sector.

Certain landforms and coastal features are more vulnerable to climate and sea level variation than others. Hence the immediate aim of this project was to determine the vulnerability of landforms on the Mid-West coast to changing weather and oceanographic conditions, including projected changes in climate. The determination involved assessment of aerial photography of coastal landforms between North Head and Nunginjay, site visits and a review of available meteorologic and oceanographic information. Interpretation of the information gathered was intended to identify vulnerable locations within the Study Area and assist decision-making regarding the location of any proposed coastal development and for coastal management purposes.

The structure and formation of landforms and coastal features between North Head and Nunginjay Springs Coast North is tied to rock outcrops along the shore as well as the presence and shape of the nearshore reef system. Coastal limestone forms much of the coast but merges with sandstone north of Bluff Point. This bedrock, geological control was used to identify discrete sediment cells where changes to landforms in one part of a cell were highly likely to affect the remainder of the cell but with potentially limited affect on adjoining cells. Sixty four cells were identified along approximately 160 km of coast. Potential relationships between sand dune ridges (barriers) and the underlying bedrock topography were determined where apparent; landform patterns comprising the dune barrier systems identified; and individual landforms described for each cell. The scales of description respectively correspond to scales used in the compilation of coastal management strategies and plans.

Landform vulnerability was estimated as a combination of the susceptibility of the geological structure supporting the landforms to environmental change and the current condition of the landforms as indicated by existing evidence of erosion. Together, a geological structure and the landforms it supports define a land system. The assessment involved consideration of the integrity of the geological or geomorphologic structures of land systems and the condition or stability of the landforms supported. Susceptibility rankings were determined from values assigned to marine topography near the shore; the shape of the shoreline; coastal orientation; and the prevailing type landforms present in the cell. Similarly, instability rankings were based on the proportion of rocky versus sandy seabed; beach type and/or beachface shape; whether the frontal dune complex has been eroded; and an overall estimate of vegetation cover on the sand barrier. The analysis was intended to be indicative rather than prescriptive and has application for strategic planning purposes as a first step to more detailed risk assessment procedures.

Land System Susceptibility

Sixty four cells were identified in the analysis. Three cells, between Connell Road and the Marina at Geraldton were not considered. They include Geraldton Port and engineered sections of coast. The overall results for all other coastal cells in the Mid-West revealed a substantial proportion, 39 of the 61 (64%) cells examined were moderately susceptible to environmental change. Seventeen cells (28%) had a landform assocation with a low susceptibility; and five cells (8%) were highly susceptible.

Tracts of land having low susceptibility to environmental change were most common south of Flat Rocks. They occurred between South Fisherman and South Bay, Webb Islet to Cliff Head, Leander Point to Seven Mile Beach, Bookara South and Headbutts and immediately north of the Bowes River. These were areas where the coast was protected by offshore reef, rock typically outcrops along the shore and the dune barrier was likely to be perched on a rock surface above High Water Level.

Sediment cells considered highly susceptible to environmental change due to unconsolidated landforms, lack of bedrock support and exposure to metocean forcing were not common in the Study Area. Exceptions occurred along the Geraldton coast between the Marina and St Georges (Cell 44) as well as from Sandalwood Bay to Yanganooka (Cell 57). A more extensive tract of coast that was highly susceptible to change in the natural structure was the mainly cliffed coast between Bluff Point and the Murchison River (Cells 61 to 63).

Landform Stability

Estimated levels of instability for each of the cells along the Mid-West coast revealed a high proportion, fifty three of the 61 (87%) cells examined, were moderately to highly unstable. Eight cells (13%) had a low instability ranking, twenty five cells (41%) were moderately unstable and twenty eight cells (46%) were of high instability.

Sediment cells with low instability were most common on the coast south of Cliff Head. They occurred between Sandy Cape and Fishermans Islands, unsurveyed point and Webb Islet, South Illawong and Cliff Head, Pages to Connell Road and from St Georges to the Chapman River. They were areas where there the shore was sheltered by inshore reefs and/or rocky pavement, the frontal dune complex was intact and the barrier dunes well vegetated.

Combinations of some of the following factors indicated current levels of landform instability: the inshore seabed was bare sand; beaches were commonly subject to high wave conditions or part of a barred river mouth; there was no foredune and the frontal dune was scarped; and vegetation cover was low and /or mobile sand sheets were present on the barrier. Cells having all or some of these criteria were considered to have high instability. They included tracts between Cliff Head and Leander Point, Nine Mile Beach and Headbutts, Duncans Pool to Cape Burney South and from the Bowes River to Red Bluff. Several isolated cells had landforms with a high level of instability. These included cells with southern boundaries at Separation Point, the Marina, Chapman River and the Murchison River.

Vulnerability

Vulnerability is a combination of landform association susceptibility to change due to metocean forcing and landform instability. A cell ranked at one level is highly likely to contain components of susceptibility and/or instability ranked at another. In particular, a cell ranked at a moderate level may have elements that are highly susceptible to change in the metocean regime and/or has landforms that are currently unstable. The qualification is particularly important at increasingly broader spatial scales in the land system hierarchy where a wider range of land systems and landforms is included at each compartmental scale.

Cells with a high vulnerability ranking were areas where the potential affect of metocean processes was considered a major constraint to rural-urban development due to low integrity of the natural structures, poor natural resilience and potentially require high ongoing management requirements. Development in a cell with high vulnerability is highly constrained.

An exception is where large-scale infrastructure may require coastal access (eg. for marine-based industries, major harbours or port facilities). Detailed geotechnical investigation (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique), sediment budget analysis (approximate volumetric rates of sediment transport including sources and sinks) and numerical modelling (such as wave, current and sediment transport modelling to provide further context for the volumetric rates of sediment transport) are recommended as the basis for establishment of such infrastructure.

The overall results for the Mid-West coast indicated four (6.5%) of the 61 cells examined had a low level of vulnerability; fourteen (23%) were of low-to-moderate vulnerability; seventeen (28%) were moderately vulnerable; twenty two (36%) were of moderate-to-high vulnerability and four (6.5%) had a high vulnerability.

At a broad, regional planning scale, distinct landform patternsweare apparent in each of the secondary compartments occurring in the Study Area, each characterising the structural compartment in which it occurred. The prevailing features of the secondary compartments were as follows:

1. The secondary compartment between South Illawong and Cliff Head with the lowest susceptibility to change. Its vulnerability and instability rankings were both low. Continuous offshore reef shelters much of the SW facing shore and much of the shoreface is shallow. Low-energy reflective beaches are inset between outcrops of rocky shore. Landward, the perched barrier is comprised of nested parabolic and blowout dunes. These are well vegetated away from the frontal dune ridge.

2. Coastal vulnerability rankings in two secondary compartments between North Head and South Illawong, and from Leander Point to Nine Mile Beach have an overall low to moderate ranking.

   Between North Head and South Illawong, the individual cell rankings range from low to moderate. Cells in the central part of the compartment, between South Bay and unsurveyed point, display moderate levels of susceptibility and instability, as does the coast between North Head and Sandy Cape. These are areas with a variety of landforms including cuspate forelands and tombolos as well as perched beaches and small embayments. In places, the frontal dune ridge is scarped along the shore and foredunes are either absent or discontinuous. The episodic transgressive dune barriers have small blowouts and some mobile sand sheets. There is evidence of disturbance related to vehicle access tracks.

   Sheltered beaches; most perched on rock platforms are found along the coast between Leander Point and Nine Mile Beach. The beaches front episodic transgressive barriers and foredune plains with high frontal dunes. The foredunes and frontal dunes have been locally scarped and cut by access tracks. The combination of a low susceptibility to change and a moderate level of instability gives the secondary compartment its overall susceptibility ranking.

3. Two adjoining secondary compartments have a moderate vulnerability ranking: Cape Burney South to Glenfield and Glenfield to the Bowes River. The former includes the shores of the Tarcoola Embayment and Champion Bay which are separated by the Point Moore Tombolo. Diversity of landform, in part underlain by coastal limestone and generally overlain by urban development in the Geraldton area has given rise to a wide range of instability rankings. High instability is notable between Separation Point and Point Moore as well as between the Chapman River and Glenfield. The coast between the Marina and St Georges is both highly susceptible to change due to its exposure and has a high instability ranking. It is a severely eroded shore.

   The character of the coast changes between Glenfield and the Bowes River. The inner continental shelf and shoreface are narrower than further south; much of the shore is stabilized by rock platforms and low bluff; the beaches are increasingly exposed with distance north; barrier forms included episodic transgressive dunes or narrow foredune plains abutting an older barrier complex; and there are numerous ORV tracks in the area. The vulnerability ranking is derived from moderate levels of susceptibility and instability in the three cells comprising the compartment.

4. The remainder of the compartments subject to an overall moderate to high level of vulnerability to environmental change. This is apparent in three geographic areas.

   First, a wide transgressive barrier with nested parabolic dunes and mobile sand sheets is present between Cliff Head and Leander Point . It has formed landward a sandy inshore and has exposed beaches with bars and rips along a rhythmic shoreline. In many places, the frontal dunes have been scarped and a discontinuous foredune has formed seaward of the scarp face. These characteristics indicate moderate levels of vulnerability and a high level of instability.

   Second, from Nine Mile Beach to Cape Burney South much of the coast is stabilized by a high rock platform and beaches are either perched on the platform or occur in small embayments between rock outcrops. The inshore reef pattern alters and the degree of exposure increases with distance north. As a result the susceptibility of the cells in the compartment is low in the southern and moderate in the northern part of the compartment. In contrast to this the coastal barrier is high, narrow and incorporates active blowouts, mobile sand sheets, eroded frontal dunes and off road vehicle tracks which indicate a high level of landform instability.

   Third, the three compartments north of Bowes River contain extensive reaches of rocky coast with cliffs and/or shore platforms. The susceptibility of cells within the compartments is mainly moderate, although the cliffed coast between Bluff Point and the Murchison River adjoins a deep inshore and is potentially highly susceptible to erosion at a seabed level. Low lagoonal shores landward of exposed linear reefs at Horrocks, Port Gregory and along the coast Eagles Nest to Waygoe Well are indicative of long-term coastal erosion and in many places the coast is backed by mobile dunes and sand sheets. Correspondingly, the compartment has a high instability ranking.

WEB SUMMARY

Certain landforms and coastal features are more vulnerable to climate and sea level variation than others. Hence the immediate aim of this project was to determine the vulnerability of landforms on the Mid-West coast to changing weather and oceanographic (metocean) conditions, including projected changes in climate. Information was gathered on coastal landforms and coastal processes to identify vulnerable locations and assist decision-making regarding proposed coastal development and for coastal management purposes.

The structure and formation of landforms and coastal features between North Head and Nunginjay Springs Coast North is tied to rock outcrops along the shore as well as the presence and shape of the nearshore reef system. Coastal limestone forms much of the coast but merges with sandstone north of Bluff Point. The bedrock geological control was used to identify discrete sediment cells where changes to landforms in one part of a cell were highly likely to affect the remainder of the cell but potentially with limited affect on adjoining cells. Sixty four cells were identified along approximately 160 km of coast. Potential relationships between the sand ridges (barriers) and the underlying coastal limestone topography were determined; landform patterns comprising the dune systems identified; and individual landforms described for sixty one of the cells. The remaining three cells include the engineered environments at Geraldton, including the port and town beach. The scales of description respectively correspond to scales used in the compilation of coastal management strategies and plans.

Landform vulnerability was estimated as a combination of the susceptibility of the geological structure supporting the landforms to environmental change and the current condition of the landforms as indicated by existing evidence of erosion. Together, a geological structure and the landforms it supports define a land system. The assessment linked the integrity of the geological or geomorphologic structures of land systems and the condition or stability of the landforms supported in a matrix to estimate five grades of vulnerability (Figure A). Susceptibility rankings were determined from values assigned to marine topography near the shore; the shape of the shoreline; coastal orientation; and the prevailing type landforms present in the cell. Similarly, instability rankings were based on the proportion of rocky versus sandy seabed; beach type and/or beachface shape; whether the frontal dune complex was eroded; and an overall estimate of vegetation cover on the sand barrier. The analysis was intended to be indicative rather than prescriptive, with applications for strategic planning purposes as a first step to more detailed risk assessment procedures.

Results included the location of cells, which were named after their southern boundaries, and the estimated vulnerability of each cell as shown in Table A and Figures B and C. Vulnerability rankings determined on a five-point scale for each sediment cell indicated four (6.5%) of the 61 cells examined had a low level of vulnerability; 14 (23%) were of low-to-moderate vulnerability; 17 (28%) were moderately vulnerable; 22 (36%) were of moderate-to-high vulnerability and four (6.5%) had a high ranking. More detail is available from the full technical report *The Mid-West Coast, Western Australia: Shires of Coorow to Northampton. Geology, Geomorphology & Vulnerability*.

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

KEY

Combined estimate of vulnerability

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

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

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

Table A: Susceptibility, Instability and Vulnerability Rankings for Each Cell

Cell	Southern Boundary of Cell	Susceptibility	Instability	Vulnerability
64	Murchison River	M	H	M-H
63	Red Bluff	H	M	M-H
62	Pot Alley	H	H	H
61	Bluff Point	H	H	H
60	Waygoe Well	M	H	M-H
59	Waygoe Well S.	M	H	M-H
58	Yanganooka	M	H	M-H
57	Sandalwood Bay	H	H	H
56	Shoal Point	M	H	M-H
55	Eagles Nest	M	H	M-H
54	Broken Anchor Bay	M	H	M-H
53	Menai Cliffs	M	H	M-H
52	White Cliffs	M	H	M-H
51	Whale Boat Cove	M	H	M-H
50	Bowes River	L	H	M
49	Coronation Beach	M	M	M
48	Buller	M	M	M
47	Glenfield	M	M	M
46	Chapman	M	H	M-H
45	Saint Georges	M	L	L-M
44	Marina	H	H	H
43	Geraldton East	Not assessed		
42	Geraldton West	Not assessed		
41	Connell Road	Not assessed		
40	Pages	M	L	L-M
39	West End	M	M	M
38	Point Moore	M	M	M
37	Separation Point	M	H	M-H
36	Cape Burney N.	M	M	M
35	Greenough North	M	M	M
34	Cape Burney South	M	H	M-H
33	West Bank	M	H	M-H

Cell	Southern Boundary of Cell	Susceptibility	Instability	Vulnerability
32	Phillips Road Coast	M	H	M-H
31	Lucys	M	H	M-H
30	Duncans Pool	M	H	M-H
29	Flat Rocks	M	M	M
28	Headbutts	L	M	L-M
27	Shire Boundary	L	H	M
26	Bookara South	L	H	M
25	Nine Mile Beach	M	H	M-H
24	Seven Mile Beach	L	M	L-M
23	Harleys Hole	L	M	L-M
22	Dongara North	L	M	L-M
21	Leander Point	L	M	L-M
20	South Leander Point	M	H	M-H
19	White Point	M	H	M-H
18	Cliff Head	M	H	M-H
17	North Knobby Head	L	L	L
16	South Illawong	L	L	L
15	Gum Tree Bay	L	M	L-M
14	Coolimba	L	M	L-M
13	Tailor Bay	L	M	L-M
12	Leeman	L	M	L-M
11	Webb Islet	L	L	L
10	unsurveyed point	M	L	L-M
9	Little Anchorage	M	M	M
8	Point Louise	M	M	M
7	Greenhead	M	M	M
6	South Bay	M	M	M
5	Fisherman Islands	L	M	L-M
4	South Fisherman	L	L	L
3	Sandy Cape	M	L	L-M
2	Sandland	M	M	M
1	North Head	M	M	M

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

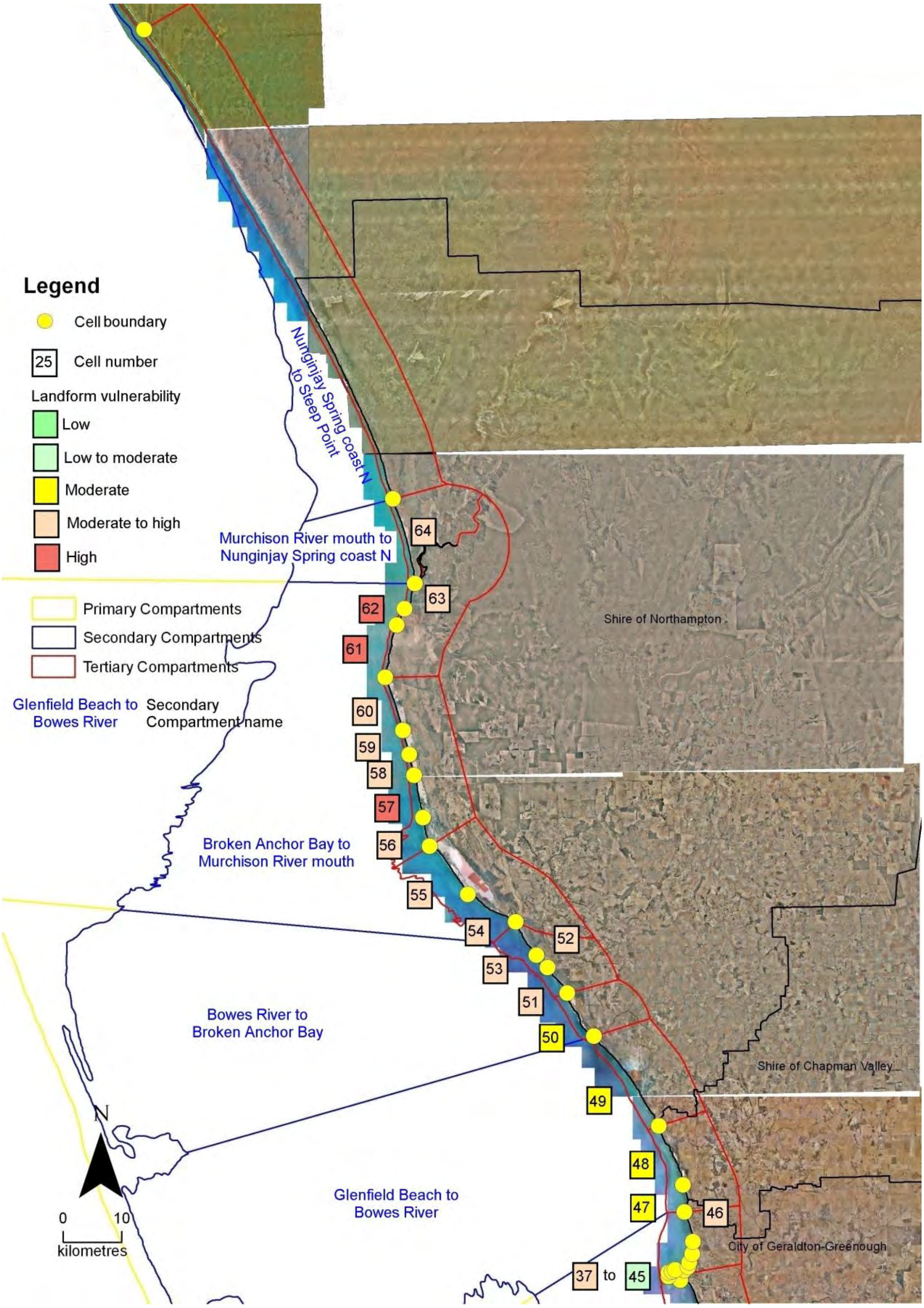

Figure B: Estimated Vulnerability Rankings for the Mid-West Coast – Point Moore to Nunginjay Spring Coast North

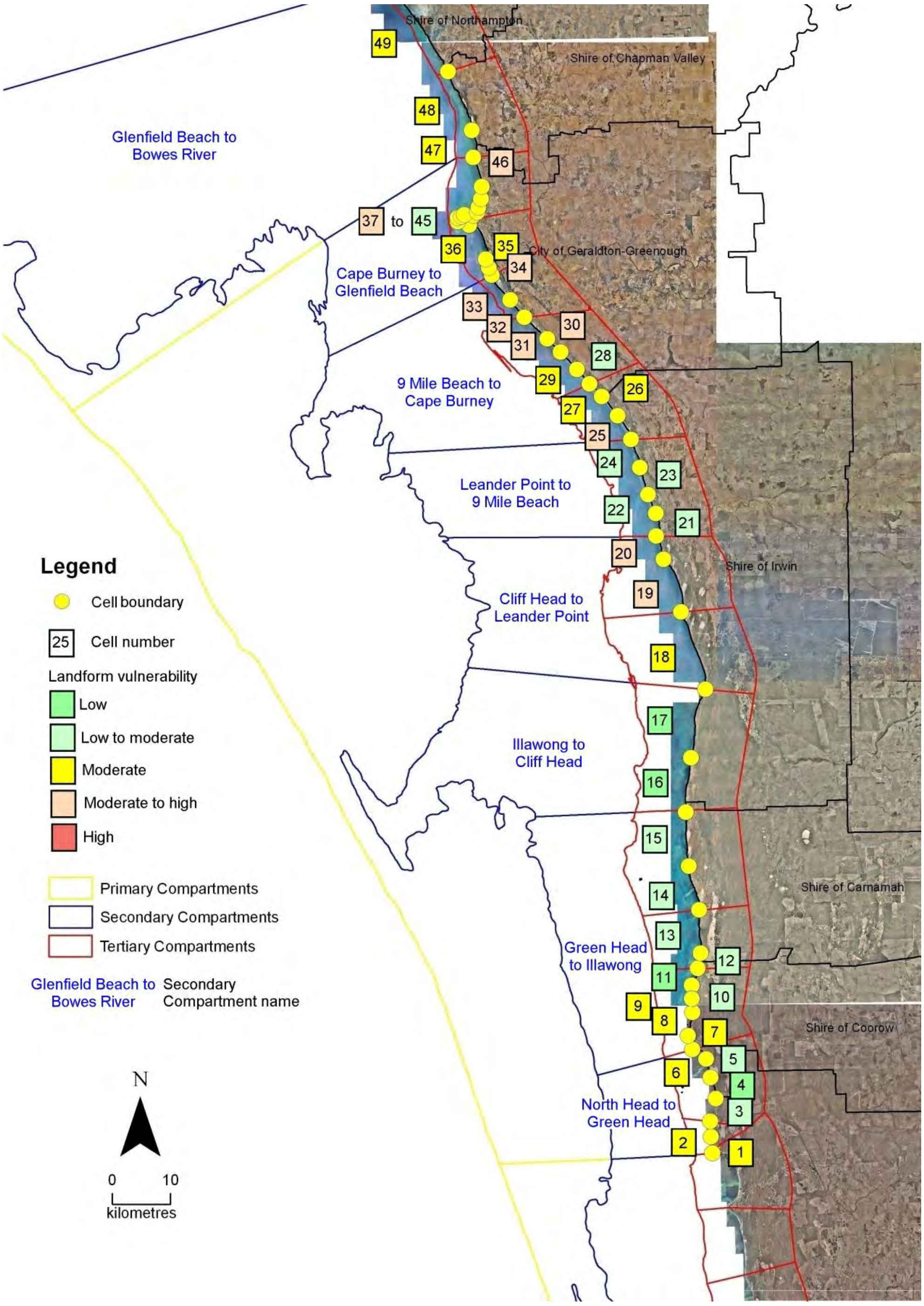

Figure C: Estimated Vulnerability Rankings for the Mid-West Coast – North Head to Coronation Beach

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

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1. Introduction

This project identifies the landforms that are likely to alter in response to changes in meteorologic and oceanographic processes along the coast between North Head and Nuningjay Spring Coast North (north of Kalbarri; Figure 1-1). The study is intended to provide input to strategic planning, and also facilitate more detailed local-scale risk assessments. Changes of interest are those occurring over two time scales: observable landform changes presently taking place over sub-decadal time scales; and those projected to occur over a planning horizon of 100 years. Application of this project requires additional information to develop mitigation strategies. Further investigations will be required to identify and assess the magnitude and timing of specific risks to existing and planned uses of the coast as well as for development of strategies and detailed plans for risk management and mitigation.

1.1. AIMS AND OBJECTIVES

Nationally, Western Australia boasts an enviable diversity of coastal landforms. The diversity includes areas of outstanding beauty such as the World Heritage Area at Shark Bay (Department of Environment and Conservation: DEC 2008) as well as low lying areas in the Pilbara (Semeniuk 1996a) and estuaries of the south west coast (Brearley & Hodgkin 2005) that are prone to inundation by flooding and storm surge (Department of Climate Change: DCC 2009). This has been acknowledged through formulation and adoption of the *Coastal Zone Management Policy for Western Australia* (Western Australian Planning Commission: WAPC 2001) and the *Western Australian Coastal Management Plan* (WAPC 2002). The *Coastal Zone Management Policy* provides objectives for management of the coastal zone and the multiple uses it supports, with the *Coastal Management Plan* providing direction for where the policy should be applied. Operating under this policy and plan are the State Coastal Planning Policy SPP2.6 (WAPC 2003) that provides advice on calculating coastal setbacks and the Coastal Protection Policy (Department for Planning & Infrastructure: DPI 2006) which provides a framework for allocation of funding for erosion mitigation works through the Coastal Protection Funding Program. The policies are founded on long-standing governance of the coast by State and Local Government authorities and the well-founded interest and commitment of coastal communities.

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

Examination of the coastal geomorphology between North Head and Nuningjay Spring Coast North involved assessment of aerial photography of the study area, site visits and a review of relevant and available metocean information. It was conducted at two spatial scales:

- First land systems and major landform components comprising discrete coastal compartments of the Study Area (Figure 1-2) were identified and for the purposes of the report they provide the geologic framework in which sediment cells are recognised. *Coastal compartments* are natural structural features. They are comprised of large scale geologic and geomorphologic features subject to significant changes over decades to millennia. The boundaries are identified in this report.
- Second, *sediment cells* along the coast were examined in more detail. Sediment cells commonly are smaller three-dimensional units (Figure 1-3 and Figure 1-4) nested within the broader compartments. In the context of this report they are identifiable at scales of 1:10,000 to 1:25,000 or larger at a more detailed local level. Cells are functionally defined by the likely movement of unconsolidated sediments between source areas and sinks via transport pathways within geologic and geomorphic boundaries. Landforms comprising the cells are likely to change in response to sub-decadal, including seasonal and higher frequency changes in metocean processes. In part the distinction between compartments and cells also is based on the potential ease of determining a sediment budget from available information. Some tertiary compartments are large sediment cells.

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

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

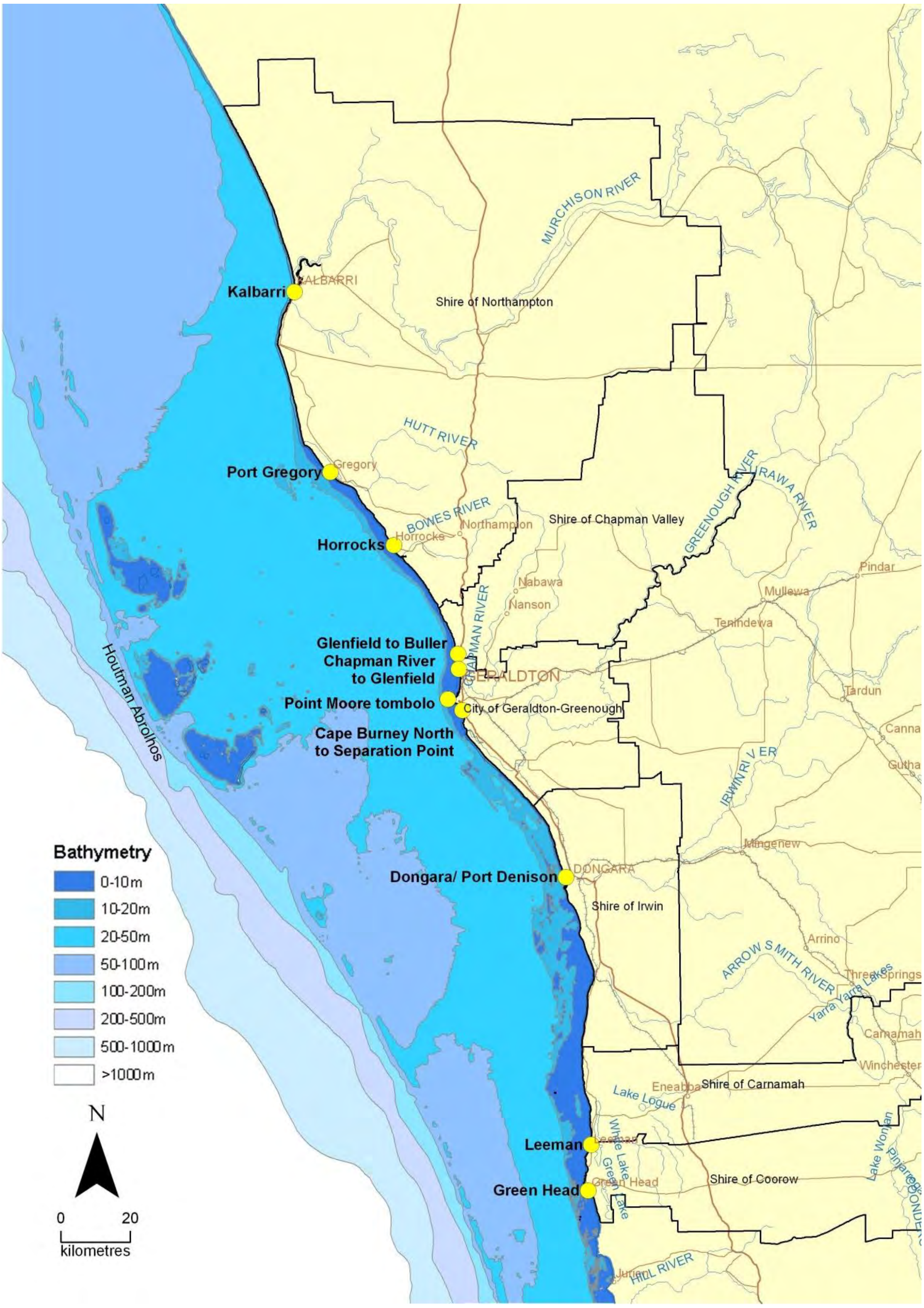


Figure 1-1: Study Area
North Head and Nuningjay Spring Coast North
Yellow dots identify Areas of Planning Interest

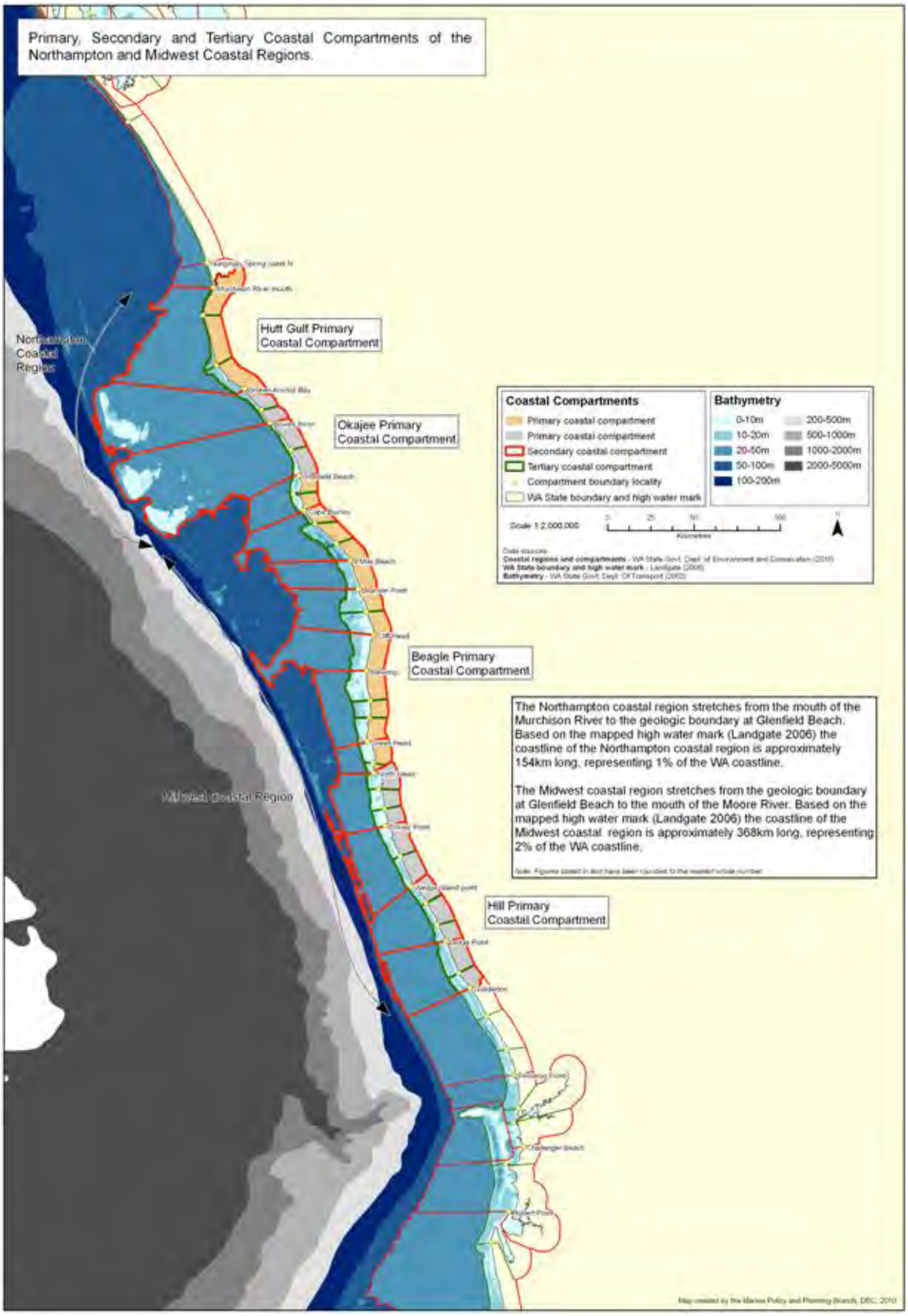


Figure 1-2: Mid-West Coastal Compartments
(Source: Eliot *et al.* 2011a)

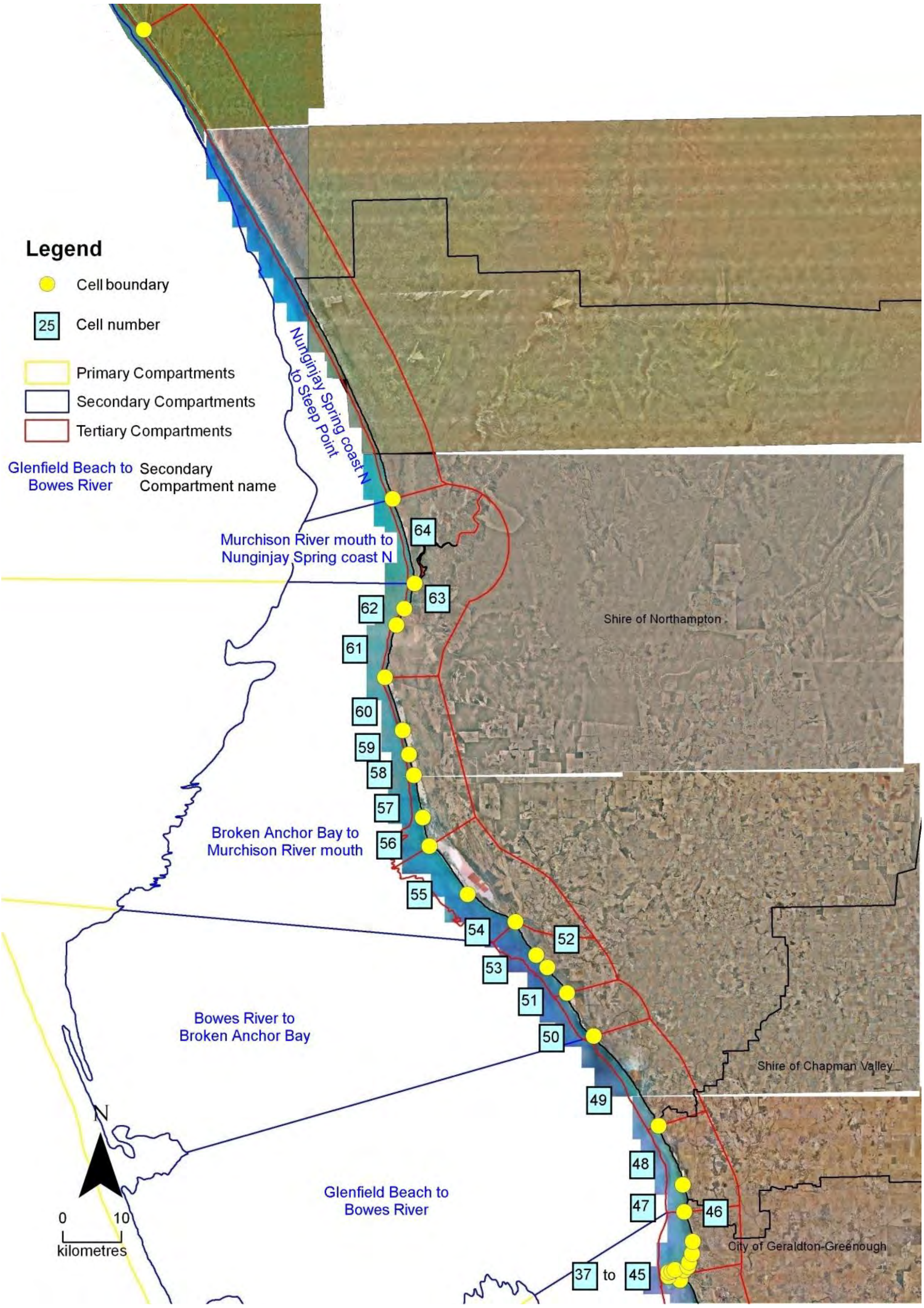


Figure 1-3: Compartments and Sediment Cells (37 – 64)

Offshore boundaries are at the 130m, 50m and 20m bathymetric contour for primary to tertiary compartments (Table 2-4) and correspond with significant geologic features and metocean conditions (Eliot *et al.* 2011a). The primary boundary follows the offshore reef

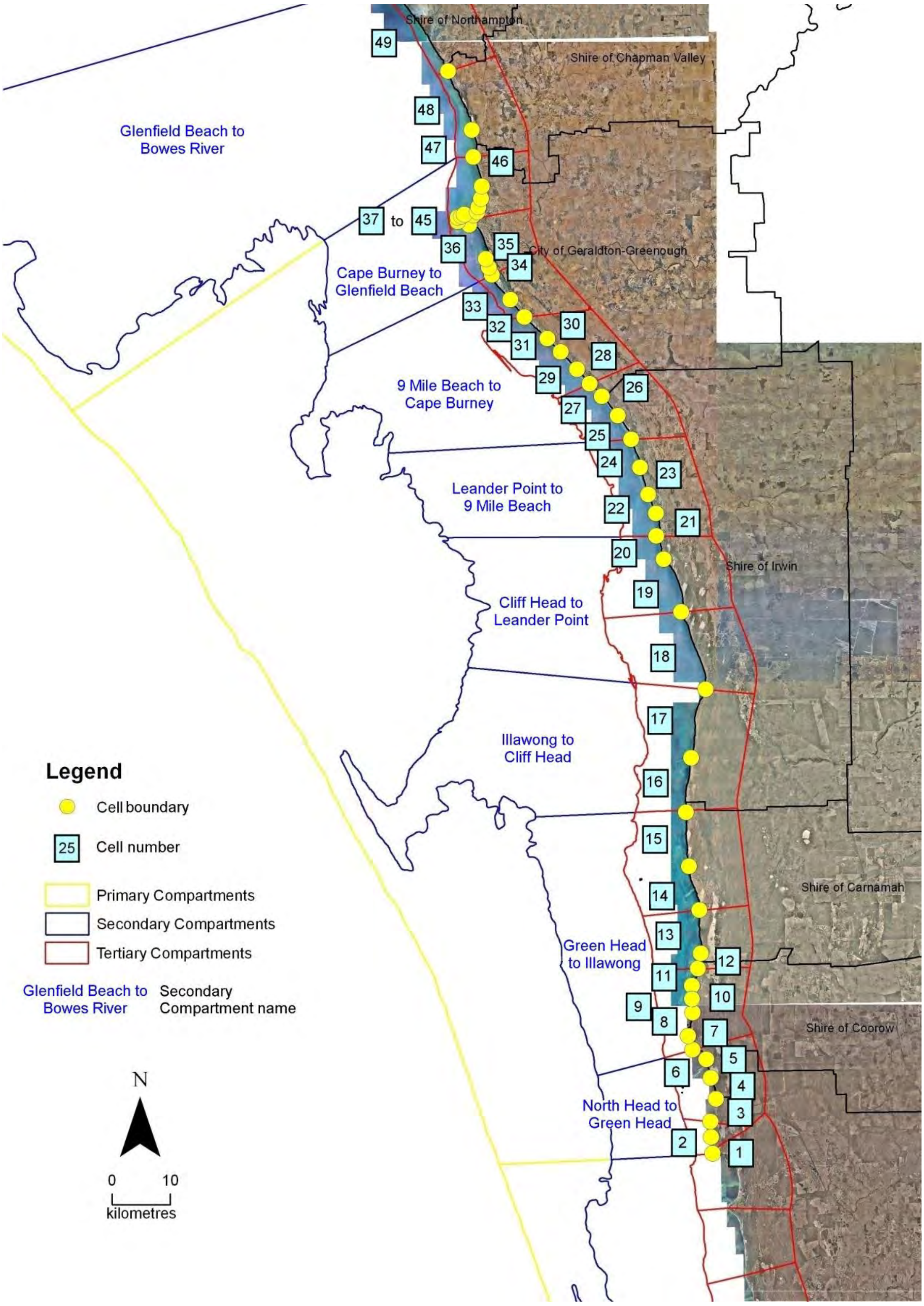


Figure 1-4: Compartments and Sediment Cells (1 – 49)
Offshore boundaries are at the 130m, 50m and 20m bathymetric contour for primary to tertiary compartments (Table 2-4) and correspond with significant geologic features and metocean conditions (Eliot *et al.* 2011a). The primary boundary follows the offshore reef

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

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

The objectives of the project are to describe the geomorphology of the coast of the Shires of Coorow to Northampton in Western Australia (Figure 1-1); determine land systems or structures that are susceptible to change over a long period; identify landforms that are currently unstable; and assess the vulnerability of different parts of the coast to projected change in metocean forcing. In turn the information presented is intended to identify the nature and degree of investigation required to support management proposals for the land system or landform under consideration.

It was intended these objectives would be met by:

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

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

1.2. TASKS

A key task in the examination of coastal land systems for strategic coastal planning in the shires of Coorow to Northampton was to provide an indicative assessment of coastal vulnerability to changing metocean processes that is consistently applicable at all planning scales, which guides potential land use and potentially has relevance to upscaling and downscaling responses to risk aversion or mitigation.

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

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

1.3. APPROACH

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

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

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

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

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

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

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

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

1.4. DOCUMENT USE

A methodology developed to assess coastal vulnerability to changes in climate and sea level has been developed at a sediment cell scale, which approximately corresponds to a 1:100,000 map scale, suitable for strategic regional planning. An overall estimate of vulnerability has been made for each sediment cell. The overall vulnerability is intended to provide an indication of the management pressures likely to accord for land-use within the cell as a whole as well as to facilitate comparison between different sectors of coast.

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

The offshore limit of the Study Area is linked by depth contour to the scale of the compartments and cells being examined. The landward limit is the boundary between recent (Holocene) and older geology and landforms. North Head has been used as the southern boundary because it separates primary compartments along the coast.

2. Methods

Coastal vulnerability was estimated as follows:

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

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

2.1. IDENTIFICATION OF PLANNING UNITS

The planning units of sediment cells are nested within a hierarchy of coastal compartments (Table 2-1; Figure 1-3; Figure 1-4). In the context of this report sediment cells are areas sharing physical features apparent at mapping scales appropriate to local and regional planning. The approach used focused on description of the structural framework provided by the geology, and to a lesser extent, large geomorphic features formed of unconsolidated sandy sediment.

Four sets of features were used to identify the alongshore boundaries of coastal compartments and sediment cells. These are listed in Table 2-2 and examples of boundaries are provided in Figure 2-1. The offshore boundaries of the compartments and cells as well as their interpretation in terrestrial coastal planning are outlined in Table 2-3. Onshore, the boundary of the compartments and cells is either the landward extent of marine and eolian sediments deposited over the past 10,000 years, during the Holocene, as the present coast developed; or approximately 500 metres landward from the rocky shoreline. At each scale, landforms and the processes affecting them (Table 2-4) provide an approach to interpretation and implementation of the State Coastal Planning Policy SPP2.6 (WAPC 2003) and/or the Coastal Protection Policy (DPI 2006).

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

Table 2-1: Compartments and Sediment Cells

Compartment			**Sediment Cell**
Primary	**Secondary**	**Tertiary**	**Primary**
ZUYTDORP: Murchison R. to Cape Inscription (Beyond Study Area)	Murchison River to Nunginjay Spring C. N.	Murchison River to Nunginjay Spring Coast North	64. Murchison River to Nunginjay Spring Coast North
HUTT: Broken Anchor Bay to Murchison River	Broken Anchor Bay to Murchison River	Bluff Point to Murchison River	63. Red Bluff to Murchison River
			62. Pot Alley to Red Bluff
			61. Bluff Point to Pot Alley
		Shoal Point to Bluff Point	60. Wagoe Well to Bluff Point
			59. Wagoe Well South to Wagoe Well
			58. Yanganooka to Wagoe Well South
			57. Sandalwood Bay to Yanganooka
			56. Shoal Point to Sandalwood Bay
		Broken Anchor Bay to Shoal Point	55. Eagles Nest to Shoal Point
			54. Broken Anchor Bay to Eagles Nest
OAKAJEE: Glenfield to Broken Anchor Bay	Bowes River to Broken Anchor Bay	Whale Boat Cove to Broken Anchor Bay	53. Menai Cliffs to Broken Anchor Bay
			52. White Cliffs to Menai Cliffs
			51. Whale Boat Cove to White Cliffs
		Bowes R. to Whale B. C.	50. Bowes River to Whale Boat Cove
	Glenfield to Bowes River	Coronation Beach to Bowes River	49. Coronation Beach to Bowes River
		Glenfield to Coronation Beach	48. Buller to Coronation Beach
			47. Glenfield to Buller
BEAGLE: North Head to Glenfield	Cape Burney South to Glenfield	Point Moore to Glenfield	46. Chapman to Glenfield
			45. Saint Georges to Chapman
			44. Marina to Saint Georges
			43. Geraldton East to Marina
			42. Geraldton West to Geraldton East
			41. Connell Road to Geraldton West
			40. Pages to Connell Road
			39. West End to Pages
			38. Point Moore to West End
		Cape Burney South to Point Moore	37. Separation Point to Point Moore
			36. Cape Burney North to Separation Point
			35. Greenough North to Cape Burney North
			34. Cape Burney South to Greenough North
	Nine Mile Beach to Cape Burney South	Phillips Road Coast to Cape Burney South	33. West Bank to Cape Burney South
			32. Phillips Road Coast to West Bank
		Headbutts to Phillips Road Coast	31. Lucys to Phillips Road Coast
			30. Duncans Pool to Lucys
			29. Flat Rocks to Duncans Pool
			28. Headbutts to Flat Rocks
		Nine Mile Beach to Headbutts	27. Shire Boundary to Headbutts
			26. Bookara South to Shire Boundary
			25. Nine Mile Beach to Bookara South
	Leander Point to Nine Mile Beach	Leander Point to Nine Mile Beach	24. Seven Mile Beach to Nine Mile Beach
			23. Harleys Hole to Seven Mile Beach
			22. Dongara North to Harleys Hole
			21. Leander Point to Dongara North
	Cliff Head to Leander Point	White Point to Leander Point	20. South Leander Point to Leander Point
			19. White Point to South Leander Point
		Cliff Head to White Point	18. Cliff Head to White Point

Compartment			Sediment Cell
Primary	**Secondary**	**Tertiary**	**Primary**
BEAGLE: continued from above	S. Illawong to Cliff Head	South Illawong to Cliff Head	17. North Knobby Head to Cliff Head
			16. South Illawong to North Knobby Head
	Green Head to South Illawong	Coolimba to South Illawong	15. Gum Tree Bay to South Illawong
			14. Coolimba to Gum Tree Bay
		Green Head to Coolimba	13. Tailor Bay to Coolimba
			12. Leeman to Tailor Bay
			11. Webb Islet to Leeman
			10. Unsurveyed Point to Webb Islet
			9. Little Anchorage to Unsurveyed Point
			8. Point Louise to Little Anchorage
			7. Green Head to Point Louise
	North Head to Green Head	Sandy Cape to Green Head	6. South Bay to Green Head
			5. Fisherman Islands to South Bay
			4. South Fisherman to Fisherman Islands
			3. Sandy Cape to South Fisherman
		North Head to Sandy Cape	2. Sandland to Sandy Cape
			1. North Head to Sandland

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

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

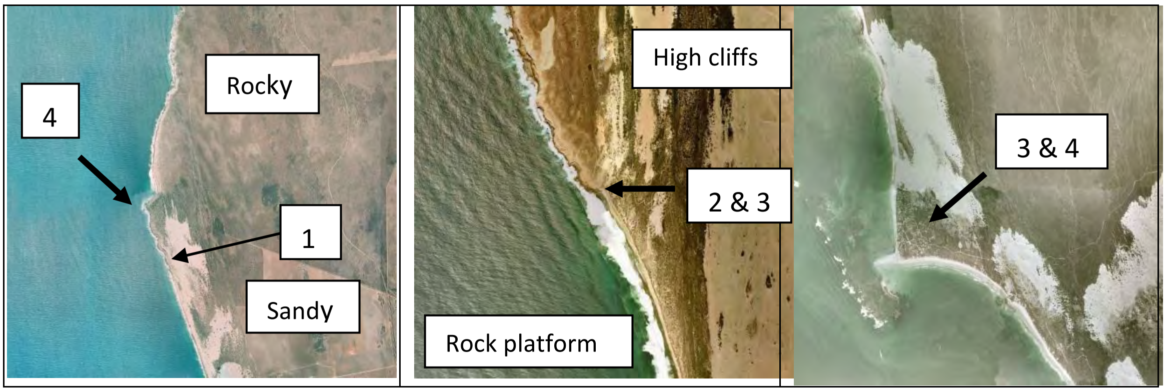


Figure 2-1: Examples of Compartment Boundaries
1 = change in geology; 2 = rock structure; 3 = geomorphic feature; and 4 = change in aspect
➞ = Primary boundary → = Secondary boundary

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

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

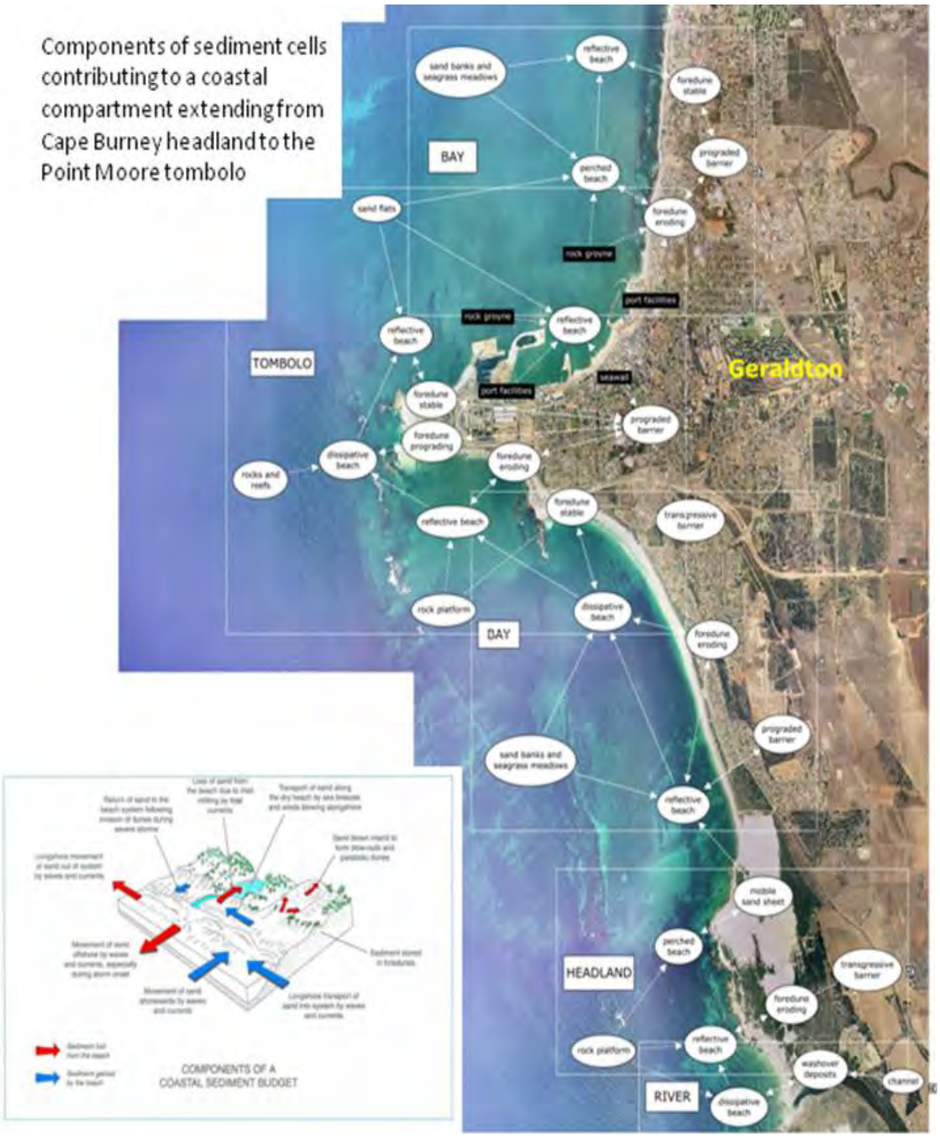


Figure 2-2: Sediment Budget Components
A Coastal Compartment Showing Components of Sediment Cells
Inset: A Conceptual Sediment Cell with Components of the Sediment Budget (WAPC, 2002)

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

Table 2-3: Offshore Boundaries of Coastal Compartments and Coastal Planning and Management Applications

Boundary (isobath)	Land System/Landform Scale and Geology	Management Application
Primary Compartments (130 metres)	Mega-scale land systems e.g. Barriers, river deltas, zeta-form beaches Geological development of the coastal plan form occurs at this scale. Marine processes affecting the inner continental shelf establish the geological setting of coastal land and its broad susceptibility to long-term erosive forces operating over decades, centuries and millennia.	The inner continental shelf is significant for marine resource planning and management because it supports a high proportion of aquatic biota fished for commercial and recreational purposes, and which demand land based infrastructure for its exploitation. Primary compartments are areas of substantial overlap between Commonwealth and State interests. Waters beyond State Water boundary at 3nm (approximately 6km) are jointly managed through an intergovernmental agreement.
Secondary Compartments (50 metres)	Meso- to Macro-scale land systems and landforms e.g. Cuspate forelands, tombolos and dune sequences Holocene, including present day, development of the coastal plan form occurs at this scale. The topographic structure of the inner continental shelf affects wave patterns and nearshore water circulation. Coastal changes are apparent at interannual to decadal time periods.	Closer to shore, this is the area of most intense use of the marine environment for commercial and recreational purposes, including recreation and tourism. Meso-scale landforms are apparent as components of coastal sediment cells and sediment budgets at this scale. They identify areas of relative coastal stability as well as susceptibility to change, and hence indicate potential problems for coastal planning and management. In this context there may be a requirement for detailed studies at a local scale.
Tertiary Compartments (20 metres)	Micro- to Meso- scale landforms. e.g. beaches, foredunes and blowouts. Inshore topography landward of the 20m isobath determines the nearshore wave regime and current patterns that drive the coastal sediment budget. It has a direct affect on the stability of coastal landforms, particularly those comprised of unconsolidated sediment. Coastal changes are apparent at seasonal and interannual to decadal scales.	The inshore waters and coastal lands are critical for provision and maintenance of marine based infrastructure (harbours and marinas). In addition to its commercial value, the area comprises a substantial proportion of State Waters and is highly significant for coastal recreation. Landforms within the tertiary components are directly related to sediment cells. They include indication of areas likely to be unstable and which may require special consideration for coastal management at a local level.
Sediment Cell (Offshore boundary linked to local sediment movement)	Micro- to meso-scale landforms associated with areas of active sediment production, mobilisation, transport and deposition. e.g. seagrass beds, scour channels, longshore troughs, beaches and mobile dunes. Micro- to meso-scale landforms comprise the major components of the coastal sediment budget and are directly related to coastal stability. Landform change may be apparent at hourly to seasonal scales.	The active components of the coast are considered under Section C of the State Coastal Planning Policy (SPP 2.6) in the calculation of requirements for the set back of development from the active beach. They are identified through changes in the beach profile, the position of the shoreline and migration of active dunes.

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

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

2.2. LAND SYSTEM AND LANDFORM IDENTIFICATION

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

- Coastal management plans (Chalmers 1983; DPUD 1993, 1994; Hammond & Eliot 1995a, 1995b; Kalbarri Townscape Committee 2003; Alan Tingay & Associates 2005a, 2005b; Koltaz-Smith 2007)
- Coastal and marine conservation plans (Department of Conservation and Land Management & Conservation Commission of WA 2004);
- Regional planning strategies (WAPC 1996, Landvision & UWA 2001; Shire of Northampton & Landvision 2006; Shire of Irwin 2007; Planwest WA & Bayley Environmental Services 2008; City of Geraldton-Greenough 2008);
- Technical reports (PWD 1976, 1983a; Gozzard *et al.* 1988; Eliot 1992; Tinley 1992; Griffin & Associates 1993; WAPC 1996b; Kern 1997; Geological Survey of Western Australia: GSWA 2000; Landform Research 2001, 2002; MJ Paul & Associates 2001; Johnson & Commander 2006; Gozzard 2011a; Tecchiato & Collins 2011); and
- Scientific papers (Mc Arthur & Bettenay 1960; Playford *et al.* 1976; Woods 1983; Hesp and Gozzard 1983; Wyrwoll 1984; Gozzard 1985; Woods *et al.* 1985; Scott & Johnson 1993; Shepherd & Eliot 1995; Sanderson & Eliot 1996, 1999; Sanderson *et al.* 1998; Sanderson 2000; Short 2005).

These provide substantial insight into the variety and distribution of landforms along the coast, and many recognise different sectors of coast based on landscape. However, few cover large tracts of coast and have adopted a compartmental or sectoral approach to landform description as a basis for planning. For example, exceptions include Hames Sharley (1988: 12) who adopted a similar approach in recommending and applying a land system approach to coastal planning for the Shire of Gingin; and Landvision & UWA (2001) which used coastal sectors to develop a strategic plan for the coast between Leander Point and the Shire of Northampton boundary on the Zuytdorp Cliffs.

Articles of particular relevance examine the geology and geomorphology of the Mid-West coast. First, Searle & Semeniuk (1985) identified the natural sectors of the Rottnest Shelf coast adjoining the Swan Coastal plain, including the southern coast of the Study Area and its marine setting between North Head and Dongara. Second, Gozzard (1985) identified, described and mapped the geology, geomorphology and land use capability of the coast between Guilderton and Green Head and is applicable to the southern part of the Study Area from North head to Green Head. Further geological surveys and land capability studies were completed for the coast between Green Head and Dongara by Hesp & Gozzard (1983) and for the Geraldton region by Langford (2000). Gozzard's work has been expanded in *WACoast* (Gozzard 2011a), part of which is incorporated in and underpins this report. Third, a detailed determination of coastal compartments based on the distribution and characteristics of sediments along the shore between the Moore River and Cliff Head was made by Sanderson (1992) and later published as Sanderson & Eliot (1996). Her findings were incorporated in a fourth document, the *Central Coast Regional Profile* (DPUD 1994), in which seven coastal sectors were identified along the coast between the Guilderton and

Dongara, four of which lie between the Moore River and Fisherman Islands. The sectors approximate the secondary compartments identified in this project, but specifically are geomorphic units. More recently Landvision & UWA (2001) recognised fifteen coastal sectors which approximate the tertiary coastal compartments identified below, in Table 2-1 for the same reach of coast.

The prior studies identify the major land systems and landforms present in the Study Area (Table 2-5) and have been used in the estimation of coastal vulnerability to metocean changes (Section 4).

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

Cross-Shore Location	Landform
(1) Nearshore Morphology	Islands Linear reefs and submarine ridges Pavements Sand banks Sand flats and seagrass meadows
(2) Landforms of the Shore	Shoreline shapes (straight, irregular, arcuate and zeta-form) Rocky coasts (cliffs, ramps and platforms) Beaches (sheltered and exposed forms)
(3) Onshore Landforms	Limestone plateaux and outcrops Foredunes Frontal dunes (blowouts and parabolic dunes) Barriers Estuaries Deltas Coastal lagoons and wetlands

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

Detailed maps of onshore landforms have been used in the assessment of vulnerability at a sediment cell scale (Figure 2-3). Apart from the application at Areas of Planning Interest (Section 6), information relevant to landuse on *specific landforms* is outside the scope of this report. However, it may be derived from several sources for local area planning:

1. It may be extracted from the instability scores for each landform type used in estimating vulnerability. However, it should be clearly recognised that the level of landform classification provides only a basic measure of potential for change, and hence the information should be used with caution.

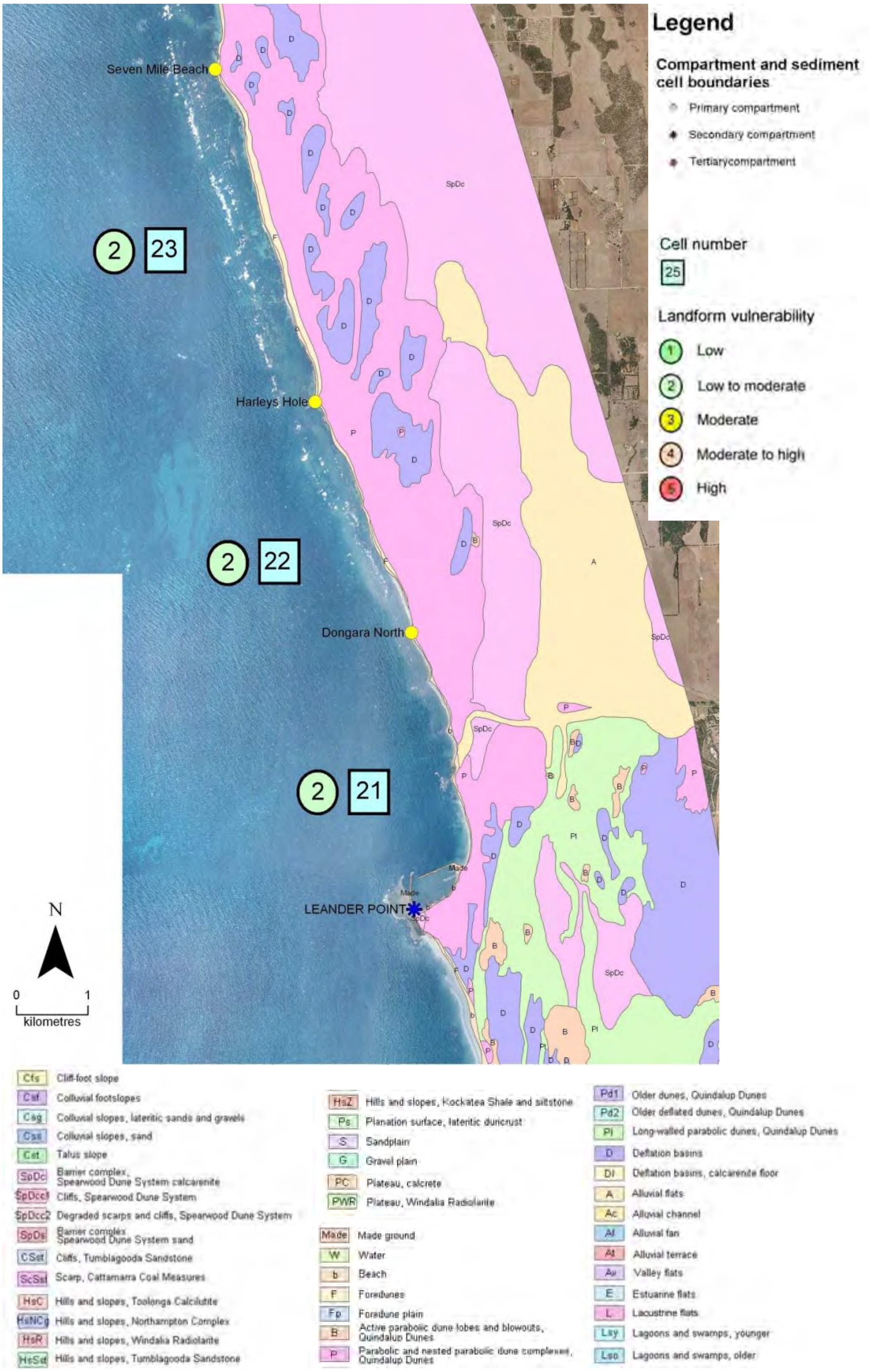


Figure 2-3: Landforms and Sediment Cells in the Vicinity of Dongara
Landform Maps for all Cells are in Appendix C.

2. In some instances, more detailed estimates of landform stability may be compiled for places of particular planning or management interest, such as green field sites nominated for future development as rural urban areas or tourism development sites. Although the high resolution landform mapping offers further spatial refinement the stability of individual landforms within such classes is quite variable. For example, frontal dunes subject to erosion by blowouts are considered to be less stable than fully vegetated, undisturbed frontal dunes in the context of the assessment, but are classified in the same landform category.

Detailed mapping of landforms and description of the conceptual models applied to them has been completed for the Western Australian coast between Cape Naturaliste and Kalbarri by the Geological Survey of Western Australia as part of the WACoast Project (Gozzard 2011a).

2.3. RANKING LAND SYSTEM AND LANDFORM SUSCEPTIBILITY AND INSTABILITY

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

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

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

Table 2-6: Criteria for Landform Susceptibility and Stability on a Mixed Sandy and Rocky Coast

(A) SUSCEPTIBILITY (Potential for structural impacts)		(B) INSTABILITY (Current changes to land surface)	
NEARSHORE MORPHOLOGY (Depth <25m)	**Rank**	**INSHORE SUBSTRATE (Depth <5m)**	**Rank**
Continuous offshore reef; shallow lagoon or shelf (platform or bank)	1	Hard rock (Granite) OR Greater than 75% reef or pavement	1
Discontinuous offshore reef; deep lagoon or shelf (platform or bank)	2	Moderately hard rock (Sandstone) OR 50 to 75% reef or pavement	2
Shallow intermittent reef or broken pavement (Depth <10m)	3	Moderately soft rock (Limestone) OR 25 to 50% reef or pavement	3
Deep intermittent reef or broken pavement (Depth >10m)	4	Soft rock (Eolianite or calcarenite) OR Less than 25% reef or pavement	4
Unconsolidated sediments Bare sand or seagrass banks	5	Bare sand: No rock outcrop	5
SHORELINE CONFIGURATION		**BEACHFACE MORPHOLOGY & PROFILE**	
Straight or seawardly convex rocky coast; made beaches	1	Sheltered - flat or segmented	1
Irregular or rhythmic shoreline	2	Sheltered - rounded (curvilinear)	2
Arcuate or zeta-form, shallowly indented	3	Exposed - reflective	3
Arcuate or zeta-form, deeply indented	4	Exposed - transitional	4
Cuspate forelands & tombolos	5	Exposed - dissipative OR Barred river mouth	5
COASTAL ORIENTATION (With respect to major storms)		**FRONTAL DUNE COMPLEX (Frontal dune and foredune)**	
South (SSE -SSW)	1	Continuous frontal dune & foredune ridges; Vegetation cover >75%	1
South West (SSW-WSW)	2	Discontinuous frontal dune & foredune ridges; Vegetation cover 50 -75%	2
North (NNW-NNE)	3	Partly scarped foredune Frontal dune vegetation cover 25-50%	3
North West (WNW-NNW)	4	Continuously scarped foredune Frontal dune vegetation cover <25%	4
West (WSW -WNW)	5	Frontal dune scarped OR mobile sand sheet OR no barrier	5
BARRIER (a) OR SAND BODY (b)		**BARRIER VEGETATION COVER**	
(a) Episodic, Transgressive Barrier OR (b) Perched dunes on supratidal or higher rock surface	1	Undisturbed dune sequence Fully vegetated (>75% cover on barrier)	1
(a) Prograded Barrier OR (b) Perched beaches on intertidal or lower rock surface	2	50 to 75% vegetation cover on barrier <25% active dunes or bare sand	2
(a) Stationary Barrier OR (b) Tombolo	3	25-50% vegetation cover on barrier 25-50% mobile dunes	3
(a) Receded Barrier OR (b) Salient & Cuspate foreland	4	<50% vegetation cover on barrier 50-75% active dunes or bare sand	4
(a) Mainland beach OR (b) Narrow spit or chenier	5	Mobile sand sheets <25% vegetation cover on barrier	5

2.4. SUSCEPTIBILITY AND INSTABILITY

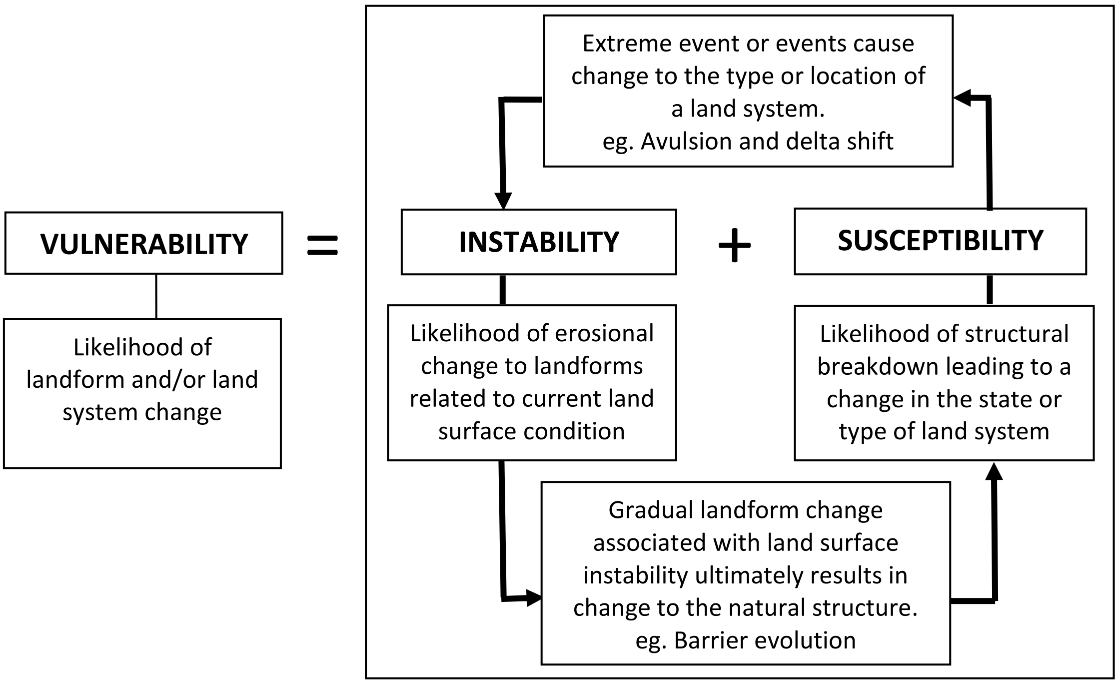
Susceptibility and instability are related concepts drawn from geological and geomorphological literature respectively describing the evolution of disparate land systems, and landform change in response to metocean processes and change in sediment supply over different intervals of time. For this study,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

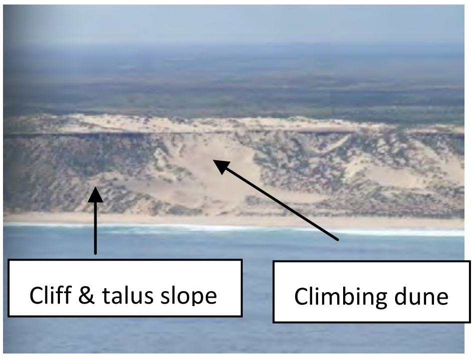
1. Deltas, estuaries and rivers: Wright (1985); Perillo (1995); Brearley & Hodgkin (2005).
2. Cuspate forelands & Tombolos: Zenkovich (1967); Sanderson & Eliot (1996); Sanderson (2000).
3. Barriers: Chapman *et al.* (1982); Cowell & Thom (1994); Roy *et al.* (1994); Hesp & Short (1999a); Masetti *et al*. (2008).
4. Beaches: Nordstrom (1980, 1992); Wright & Short (1984); Jackson *et al.* (2002); Short (2005); Eliot *et al.* (2006); Green (2008); Doucette (2009).
5. Coastal Dunes: Semeniuk *et al.* (1989); Hesp & Short (1999a, b); Hesp (2002); Houser & Matthew (2011).

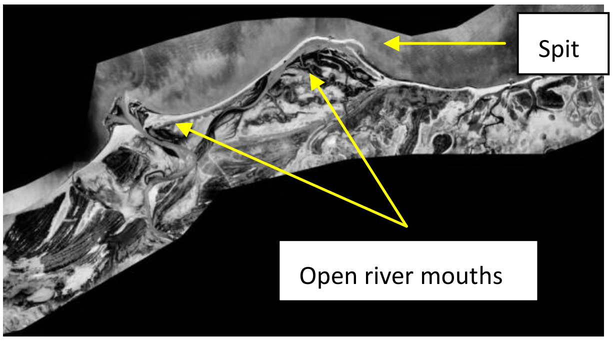
References such as those by Landvision & UWA (2001) describing land systems on the Western Australian coast and Hsu *et al.* (2008) describing topographic control of the shoreline geometry have been used where appropriate and available. However there are gaps in knowledge, particularly with respect to mixed sandy and rocky coast where the geologic framework is a major factor.

Together, the concepts of susceptibility and instability describe the *vulnerability* of coastal land systems and landforms to metocean change (Figure 2-4). Briefly, if current landform change is continued for long enough, exacerbated by natural changes in climate, or an extreme event occurs the land system on which the landform changes are taking place may reach a tipping point where the land system changes state. If a land system is susceptible to change it is highly likely that it is comprised or consists of or supports unstable, mobile landforms. For example a barrier system may be comprised of stable or unstable sand dunes where the current state of instability is evidenced by the proportion of the land surface under vegetation cover. Destabilisation of a barrier system on a stable coast may occur when barriers change from progradational to erosional forms as a result of prolonged loss of sediment from the coast (Roy *et al.* 1994; Hesp & Short 1999a; Masetti *et al.* 2008). Such large geomorphic changes have been modelled numerically, including modelling by Stive & de Vriend (1995), Cowell *et al.* (2003a, 2003b, 2006) and Stive *et al.* (2009).

The twin concepts of susceptibility and instability are linked by four key, interacting facets of the coastal environment: the geologic framework which supports the present landform systems; sediment compartments and cells in which the systems have developed; sediment supply to the cells and sediment accumulation or loss from the cells; and the resulting stability of landforms along the coast. These four components define large scale morphodynamic systems (Figure 2-5) and their interactions establish trends for changes occurring at all scales. Although linked by common metocean processes, coastal susceptibility and landform stability occur at disparate temporal and spatial scales; they have independent likelihoods of change and hence present different aspects of coastal vulnerability. These are combined in analysis ranking the vulnerability of different sections of coast, the compartments and cells.

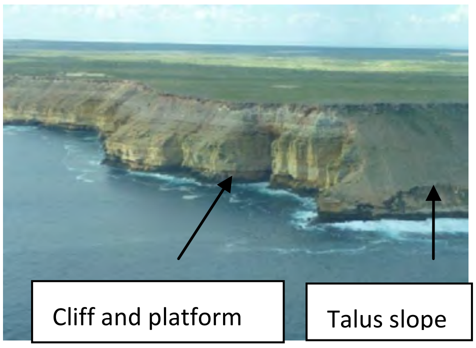


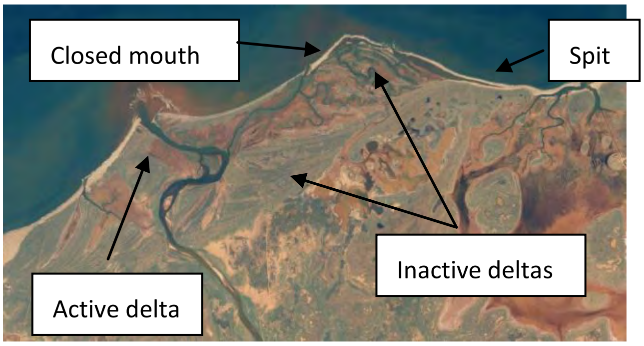




Above: Perched barrier and climbing dunes
Below: No barrier. Perched beach and old dunes

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





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

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

Figure 2-4: Instability, Susceptibility and Vulnerability

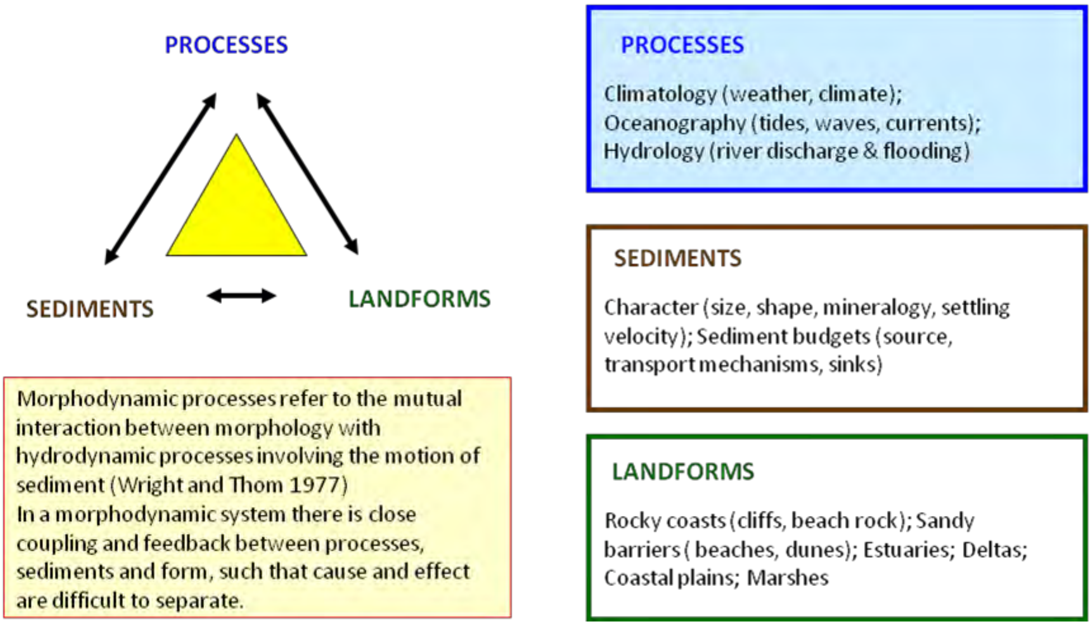


Figure 2-5: Components of a Morphodynamic System on a Sandy Coast

Viewing metocean change and landform responses at a particular scale is a matter of convenience. In reality, the environment is dynamic at all scales with slower evolutionary changes providing a long-term context for faster responses to metocean forcing (Figure 2-6). Hence, metocean processes and landform change need to be considered at multiple scales. At the broadest evolutionary scale of coastal development it is pertinent to recall the vulnerability ranking for the overall Land System, which is likely to include finer, more detailed features having a very different ranking. The level of vulnerability estimated at any scale should be set in the context of coarser and finer assessments of landform susceptibility to the natural variability of metocean drivers and the current condition (instability) of the land surface. At this scale the responses of individual landforms or landform elements to metocean events is apparent. Each scale provides an indication of management pressures likely to accord to land-use *within each* <u>*whole cell*</u> at that scale relative to others in a series described for a region or administrative coastal area.

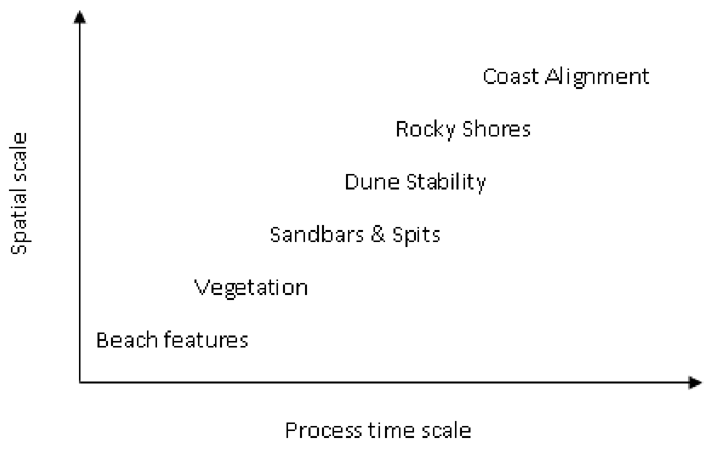


Figure 2-6: Scales of Coastal Change for Different Coastal Features

2.4.1. Land System Susceptibility

Estimation of the *susceptibility o*f land systems to large-scale change in the natural structure is based on published descriptions of coastal evolution over the past 6,000 years; however the focus of the report is on large scale landform changes likely to occur over a planning horizon of 100 years. Some of these features for barrier systems are illustrated in Figure 2-7. The generalised morphology and stratigraphy of different types of coastal sand barriers in eastern Australia has been described by Roy *et al.* (1994) with a more complex conceptual model of southern Australian barriers presented by Short (1988). More recently, Hesp & Short (1999a) have described barriers attached to or overlying cliffs. The conceptual models of Roy *et al.* (1994) and Hesp & Short (1999a) are illustrated in Figure 2-7. In this report attached barriers are referred to as perched barriers and the typology extended to include barriers overlying rock pavement, platforms and irregular bedrock surfaces as well as cliffs. These forms commonly occur around the coast of Western Australia.

2.4.2. Landform Instability

Landform *instability r*efers to the current condition of the land surface and changes taking place over short to medium time scales; those commonly occurring at less than interdecadal frequency. For the purposes of this study stability is indicated by current evidence of erosion, particularly on unconsolidated sandy coast. Examples of different levels of stability on similar landforms are illustrated in Figure 2-8 and Figure 2-9. On coastal sand barriers the instability includes historical shoreline movement, foredune washover, foredune destruction, scarping of the foredunes and frontal dunes, gullying, slumping, blow-out activity and migration of mobile sandsheets. Hesp (1988, 2002) presented a conceptual model of recurrent foredune development, destruction and reformation (Figure 2-9) which he related to shoreface processes. His observations, with those of Short (1999) are built on an understanding of the interaction of inshore, beach and dune processes, in which short-term variation in coastal stability is both affected by and affects the long-term evolution of the coast.

2.5. ESTIMATION OF VULNERABILITY

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

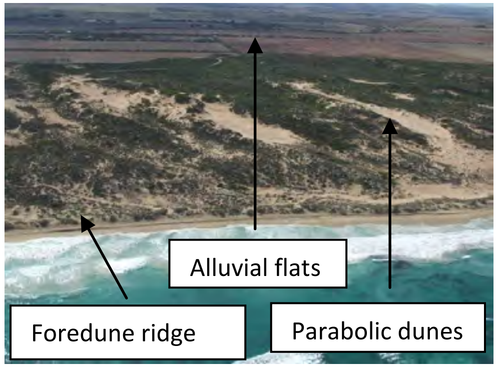
Step 1: Landform descriptions incorporating the criteria used to separately describe the susceptibility and instability of a cell were compiled for the inshore, beachface and backshore, as well as the shoreline. An example for Lancelin is provided in Table 2-7. Descriptions of landforms for each of the cells along the Mid-West coast are in Appendix D.

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

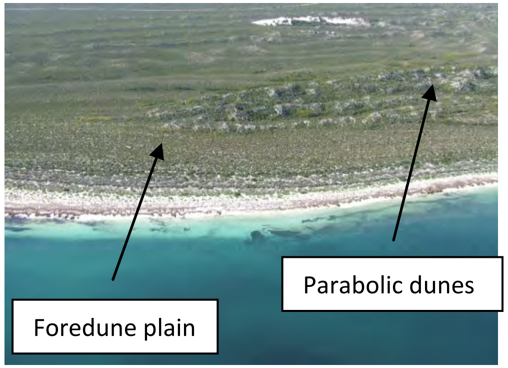
Step 3: The rank scores for the susceptibility and instability criteria were separately ordered into four zones (Table 2-8) and summed for each cell;

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

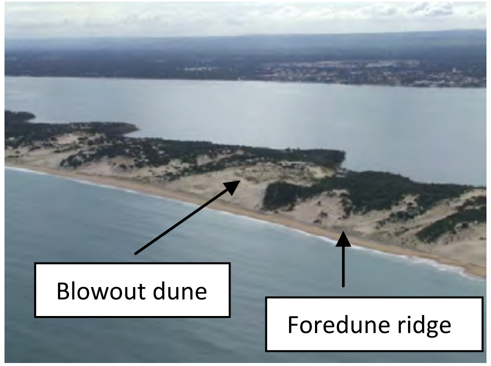
Step 5: The likelihood ranks were then combined to identify the indicative or relative vulnerability of each cell (Table 2-9). The steps used to combine the ranks are described in Section 2.6.



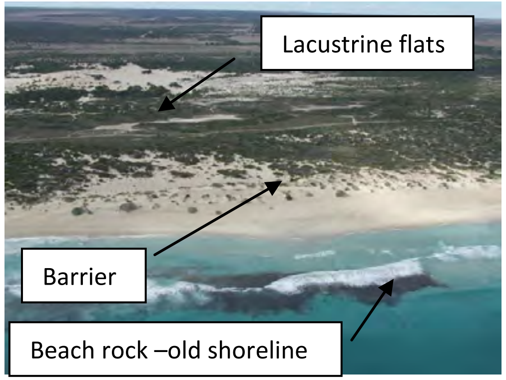
Rank 1: Episodic Transgressive Barrier
High ridge of nested blowouts and parabolic dunes. Here they abut and overlie alluvial flats.



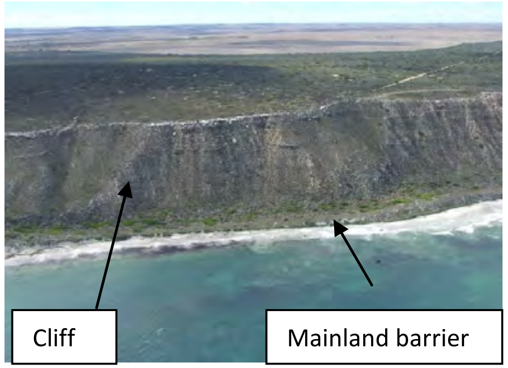
Rank 2: Prograded Barrier
Low plain comprised of foredune ridges. In this instance the plain abuts and older dune field.



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



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



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

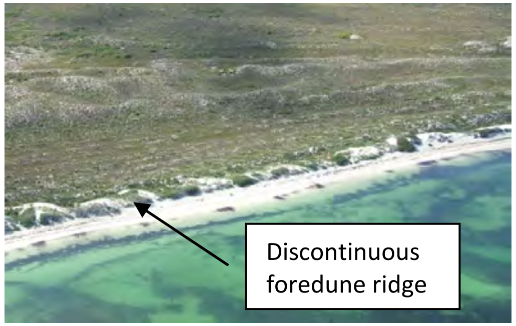
The *susceptibility* of a sandy barrier refers to the likelihood of the *natural structure* altering in response to projected changes in metocean conditions.

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

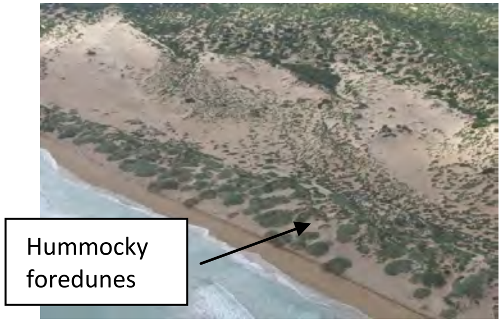
The sequence illustrated here broadly follows that described by Roy *et al* (1994)

Figure 2-7: Coastal Shoreface Structures, Land Systems and Susceptibility Rankings for Barrier Systems (After: Roy *et al.* 1994)

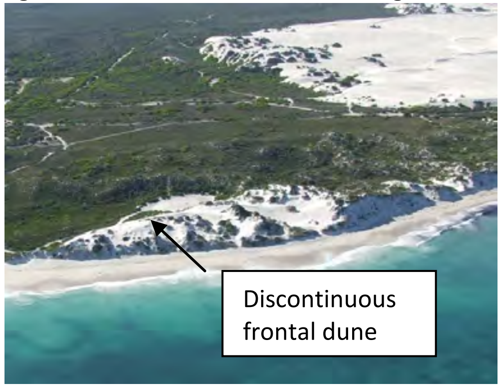
Rank 1: Continuous foredune and frontal dune ridges; Vegetation cover on the foredune ridge is >80%.



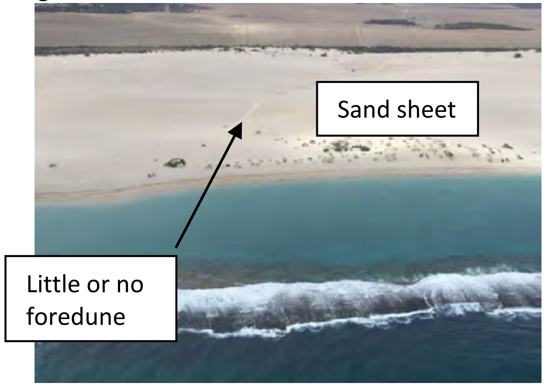
Rank 2: Discontinuous foredune ridge; small blowouts; vegetation cover on the foredune 50 to 75% cover.



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



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



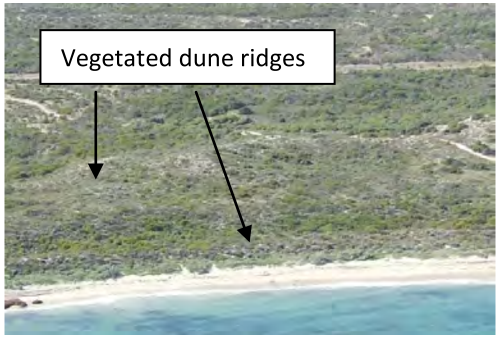
Rank 5: No foredune; scarped frontal dunes; beach directly connected to mobile sand sheet.

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

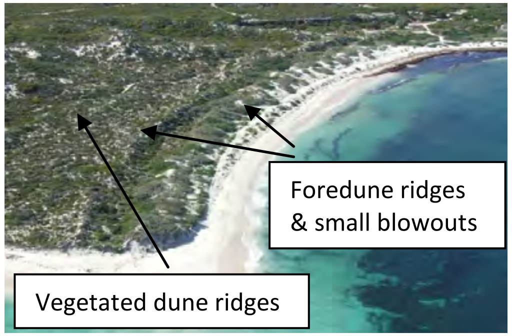
Destabilisation of dunes commonly occurs with destruction of a foredune, formation of blowouts and landward migration of the sand sheets, after which the foredune may reform. The quasi-cyclic changes take place in less than 50 to 100 years.

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

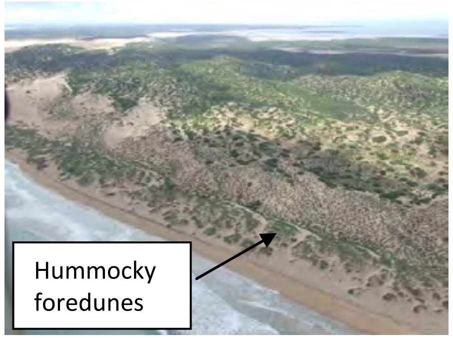
Figure 2-8: Stability of a Foredune-Frontal Dune Complex



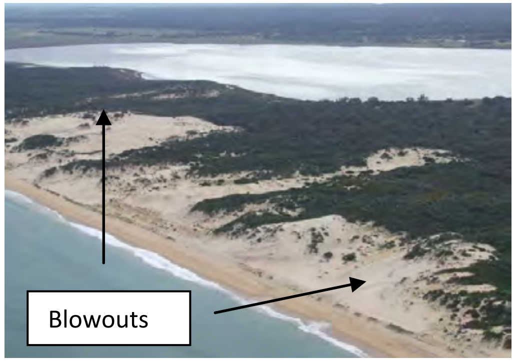
Rank 1: Gently undulating, continuous ridges of nested blowouts and parabolic dunes; Vegetation cover on the barrier is >75%.



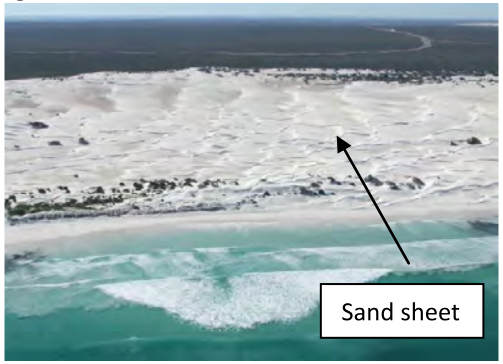
Rank 2: Complete ridges of nested blowouts and parabolic dunes with <25% active. Minor variation in vegetation cover on the barrier with >75% cover



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



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



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

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

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

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

Figure 2-9: Dune Stability on an Episodic Transgressive Barrier

Table 2-7: Example of Landform Descriptions for a Sediment Cell

Cell	S	N	INSHORE	SHORE	BACKSHORE
21	Leander Point	Dongara North	The 20m isobath is approximately 6.5km off the mouth of the Irwin River at Dongara. It is close to the southern limit of the North Bank, a broad ridge of irregular limestone reef extending NW and slightly diverging from the shore it shelters. Inshore exposure is low to moderate in the lee of Leander Reef, high in the vicinity of the river mouth; and moderate to north where further protection is provided by reef and platforms outcropping along the shore.	Away from Port Denison Harbour exposed sandy beaches face mainly WSW. The shoreline is generally straight although broken by small salients associated with outcrops of reef close to shore and by the river mouth. The beaches have a reflective profile morphology which changes to a more transitional form with distance N and increased exposure. Beaches in the northern part of the compartment are sheltered by nearshore reef.	The barrier is comprised of episodic transgressive dunes abutting or overlying discontinuous rock outcrops. Its cover is disturbed by tracking and urban development. South of the Irwin River there is a high, scarped frontal dune. This has been extensively cut at Grannys Pool near the Harbour. Low to moderate to the north. Barrier: With distance N of the river mouth the height of the scarped frontal dune with 25 to 75% vegetation cover decreases, and foredunes have formed.

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

	SUSCEPTIBILITY	INSTABILITY
1	NEARSHORE MORPHOLOGY (Depth <25m)	INSHORE SUBSTRATE (Depth <5m)
2	SHORELINE CONFIGURATION	BEACHFACE MORPHOLOGY AND PROFILE
3	COASTAL ORIENTATION	FRONTAL DUNE COMPLEX
4	BARRIER OR SAND BODY	BARRIER VEGETATION COVER

Table 2-9: Cell Susceptibility, Instability and Vulnerability Ranking for Cell at Dongara

Cell	Southern Boundary of Cell	Nearshore Morphology	Shoreline Configuration	Orientation	Barrier	Susceptibility Score	Susceptibility Ranking	Inshore Substrate	Beachface Profile	Frontal Dune	Barrier Vegetation	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability Ranking
21	Leander Point	3	2	3	1	**9**	**L**	2	3	3	3	**11**	**M**	**2**	**L-M**

2.6. INTERPRETATION OF VULNERABILITY RANKING

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

- First, the susceptibility value assigned to a compartment or cell provides an estimate of the integrity of the natural structures based on the developmental state of similar natural structures elsewhere. This enables comparative estimate of the likelihood of change over a 100 year planning horizon for compartments or cells within the coastal area of interest. The implications of the comparison in which the susceptibility of each compartment or cell is assigned a low, moderate or high likelihood of occurrence are shown in Table 2-10a.

- Second, landform instability is comparatively ranked according to the current state of the land surface in each compartment or cell, which provides an estimate of the likelihood of landform change within the next decade. Again, the estimates are assigned a low, moderate or high likelihood of occurrence and are shown in Table 2-10b.
- Third, for each compartment or cell the susceptibility and instability ranks are combined in a matrix in which the combined likelihood of short to long term changes provide a five-fold estimate of vulnerability (Figure 2-10). In turn the vulnerability rankings derived from the matrix have been interpreted as a combination of those for susceptibility and instability (Table 2-11).

Table 2-10: Recommended Consequences for Coastal Management

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

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

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

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

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

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

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

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

Figure 2-10: Indicative Vulnerability Matrix for a Mixed Sandy and Rocky Coast Based on Combined Estimates of Risk for Susceptibility and Instability

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

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

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

<table>
<tr><th colspan="2">Susceptibility</th><th colspan="2">Instability</th><th colspan="3">Vulnerability</th></tr>
<tr><th></th><th>Implications</th><th></th><th>Implications</th><th></th><th>Risk</th><th>Rationale</th></tr>
<tr><td>L</td><td>A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.</td><td>L</td><td>Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).</td><td>L</td><td>Coastal risk is unlikely to be a constraint for coastal management.</td><td>The site has a good combination of integrity of natural structures, natural resilience and low management requirements.</td></tr>
<tr><td>L</td><td>A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.</td><td>M</td><td>Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).</td><td rowspan="2">L-M</td><td rowspan="2">Coastal risk may present a low constraint for coastal management.</td><td rowspan="2">The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.</td></tr>
<tr><td>M</td><td>Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management.
Detailed assessment of coastal hazards and risks is advised.</td><td>L</td><td>Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).</td></tr>
<tr><td>H</td><td>Natural structural features are extensively unsound.
Major engineering works are likely to be required.</td><td>L</td><td>Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).</td><td rowspan="3">M</td><td rowspan="3">Coastal risk may present a moderate constraint for coastal management.</td><td rowspan="3">The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.</td></tr>
<tr><td>M</td><td>Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management.
Detailed assessment of coastal hazards and risks is advised.</td><td>M</td><td>Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).</td></tr>
<tr><td>L</td><td>A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.</td><td>H</td><td>Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah and Geraldton).</td></tr>
<tr><td>M</td><td>Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management.
Detailed assessment of coastal hazards and risks is advised.</td><td>H</td><td>Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah and Geraldton).</td><td rowspan="2">M-H</td><td rowspan="2">Coastal risk is likely to be a significant constraint for coastal management.</td><td rowspan="2">The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.</td></tr>
<tr><td>H</td><td>Natural structural features are extensively unsound.
Major engineering works are likely to be required.</td><td>M</td><td>Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).</td></tr>
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</table>

3. Regional Context: Land Systems and Landforms

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

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

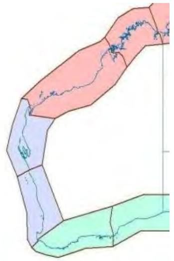
In both contexts, an objective of this report is to indicate the principal geologic, geomorphic and metocean factors contributing to the relative vulnerability of sediment cells along the coast and further develop the applications listed in Table 2-4 by integrating the marine and terrestrial components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

At a broad provincial scale, the temperate-zone coast of the shires of Coorow to Northampton is within the South West Coast Province and is subject to a Mediterranean to semi-arid climate (Figure 3-2). The province is affected by a variety of weather systems commonly including anticyclonic high pressure systems, extra-tropical cyclones, mid-latitude depressions, strong seabreezes and occasional dissipating tropical cyclones (Section 4). It extends from Cape Leeuwin to the mouth of the Murchison River at Kalbarri (Figure 3-2) and encompasses the Perth Basin (Playford *et al*. 1976).

1

Zones: Broad sectors of the Australian continent based on climate

2

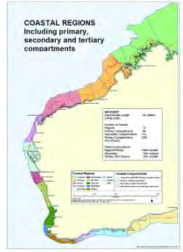


Divisions: Provides an overview of the whole state suitable for maps at scales of about 1:5,000,000

3

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

4

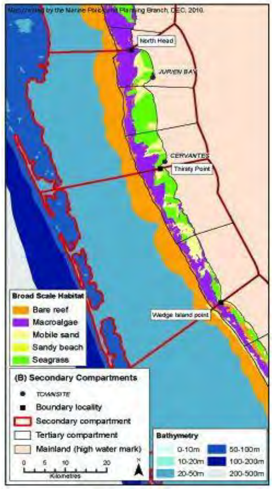


Regions: Areas with recurring patterns of landform and geology suitable for regional mapping at scales of approximately 1:250,000

5

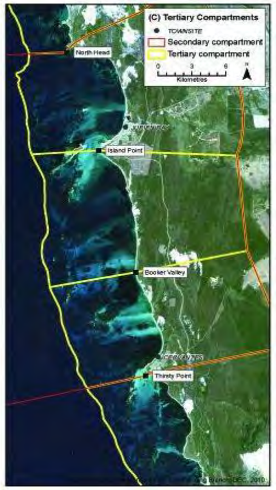
Land Systems (1):
Areas of characteristic landform patterns suitable for mapping at regional scales of 1:100,000 to 1:250,000.

6



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

7



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

8

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

Figure 3-1: Coastal Land Systems Hierarchy

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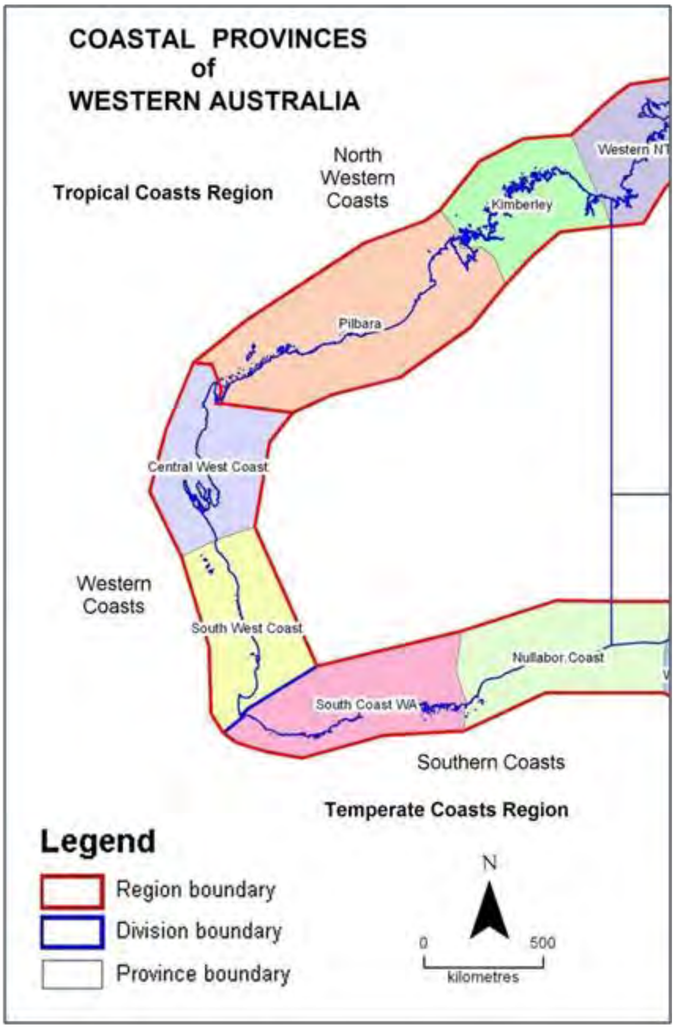


Figure 3-2: Coastal provinces in Western Australia

3.1. THE GEOLOGIC FRAMEWORK

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

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

> *"…coastlines with limited sand supplies are also significantly influenced by the geological framework occurring underneath and seaward of the shoreface. For example, many US east coast barrier islands are perched on premodern sediments. The stratigraphic section underlying these perched barriers commonly controls the three-dimensional morphology of the shoreface and strongly influences modern beach dynamics, as well as sediment composition and sediment fluxes.*
>
> *First, perched barriers consist of thin and variable layers of surficial beach sands on top of older, eroding, stratigraphic units with highly variable compositions and geometries. Depending upon composition, the underlying platforms can act as a submarine headland forcing different responses to shoreface dynamics that will dictate the nature of the shoreface profile. Stratigraphically controlled shorefaces are often composed of compact muds, limestones, or sandstones. Such lithologies exhibit a greater effect upon both the planform of barriers and morphology of the shoreface than those composed of unconsolidated materials. Second, along many parts of the inner shelf, bathymetric features that occur modify incoming energy regimes, affecting the patterns of erosion, transport, and deposition on the adjacent shorelines."*

Their observations are applicable to most of the coast of Western Australia. The observations are particularly relevant to the Mid-West coast because a large proportion of the coastal lands in the Study Area constitute Holocene dune barriers that overlie, or are perched on an irregular limestone platform of older Quaternary origin. The underlying limestone topography provides a topographic framework in which the coast is developing. Its interaction with sandy sediment and coastal processes is fundamental to the manner in which the coast has evolved and will continue to develop. It also determines the susceptibility of the coast to future environmental change.

At a local scale the nearshore ridges and depressions of the limestone on the shoreface, seaward to approximately 35metres below present sea level, 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 for two reasons: Firstly, Clearly *et al*. (1996) and others (Pilkey *et al*. 1993; Cooper & Pilkey 2004) have argued it negates application of the Bruun Rule (Bruun 1983, 1988), which has been widely applied in the calculation of setback to development on mixed sandy and rocky coast in Western Australia (WAPC 2003). Secondly, Silvester (1974), Hsu & Evans (1989) and Sanderson (2000) have discussed the roles of shoreface topography in determining the plan shape of beaches and the development of cuspate forelands. Their observations indicate it may be useful to consider the probable responses of specific coastal landforms to changing metocean processes as a more appropriate means of assessing potential coastal responses to projected environmental change in sea level or climate given that Bruun (1983) stated similar reservations with the application of his model.

3.1.1. Geology

Along the Mid-West coast the inshore seabed, beaches and dunes are comprised mainly of unconsolidated sediments of the Quindalup geological system, principally carbonate sands of Holocene age. These abut and commonly overlie older marine and aeolian sediments including the Tamala Limestone of the Spearwood System (GSWA 2000) which forms the structural framework of the coast (Searle & Semeniuk 1985), particularly south of the Chapman River.

The oldest rocks in the study area are found between Geraldton and Port Gregory. They comprise strongly deformed granitoid and sedimentary rocks of the Northampton Complex recrystallised in granulite and amphibolites facies between 1080 and 990 Ma (Myers 1990).

Between Port Gregory and Kalbarri Tumblagooda Sandstone of Ordovician age is found exposed along the coast and adjoining coastal gorges. It comprises a series of fluvial to tidal sand flat redbed facies characterised by low dips (Hocking 1991). North of the Murchison River the Tumblagooda Sandstone is overlain by Cretaceous shallow marine sandstone, radiolarite, and limestone.

South of Geraldton the geologic units of the coast are part of a belt 6 to 15 km wide, and have been assigned to the Safety Bay Sand (Quindalup Dune System) and Tamala Limestone (Spearwood Dune System). The Tamala Limestone (Playford *et al.* 1976) consists of medium- to coarse-grained calcarenite and variable amounts of quartz sand. It was deposited in the middle to late Pleistocene as successive lines of coastal sand dunes. Extensive quartz sand covers the Tamala Limestone and is a residual deposit resulting from rain water solution of the calcarenite.

The Safety Bay Sand (Lowry 1974) comprises a series of parabolic dunes and relict foredune plains (cuspate forelands) in a belt adjacent to the coast and extends inland over the Tamala Limestone. The dunes are Holocene in age and derived entirely from a Holocene source with little, if any, carbonate derived from the underlying Tamala Limestone.

The world's largest industrial garnet mine is at Port Gregory which has an estimated lifetime of at least 50 years at current extraction rates. The deposits occur as high-grade placers in dune systems located adjacent to Hutt Lagoon. The high proportion of garnet in the sand is related to the area's proximity to garnet-rich gneissic rocks of the nearby Northampton Complex (Fetherston *et al.* 1997).

3.2. SEDIMENT SUPPLY

Regional coastal processes (Section 4.2) describe the potential for sediment transport to occur on the coast, without accounting for the availability of sediment and the connectivity of sediment pathways between landforms. The concept of sediment supply and availability is included in the assessment of vulnerability through the four categories for Instability (Table 2-6). There is alongshore variability within a sediment cell, with localised sources and sinks that fluctuate in capacity and function over time, including pulsational sediment supply from rivers (Section 4.2.5). The volume of available sediment is constrained by the geologic inheritance, for example, the restricted freely available sediment on beaches underlay by rock (perched beaches–Section 4.3.5) and cliffed coasts. The primary sources and sinks of sediment to the coastal landforms are listed in Table 3-1.

Landforms are connected by sediment transport pathways, and any modification to sediment transport or sediment availability is likely to have an impact on the coast. The future stability of a landform is often dependent on any updrift interference with sediment transport and stabilisation approaches, along with natural variability and changes to metocean processes. Sediment transport interference, such as the installation of a harbour facility, could result in updrift sediment starvation of the beach and inshore, which in turn starves the frontal dune, primary dune and barrier. If an eroding dune is stabilised with revegetation; or as a dune grows or forms a blowout, this can result in sediment loss for the downdrift coast. The instability of the coast is considered with regard to the available sediment, including the vegetation coverage of the dune and barrier, with considerations of landform connectivity required when assessing future instability.

Much of the unconsolidated sediment along the coast is calcareous Quindalup sand. It is largely skeletal, shell material recently produced in seagrass meadows and algal communities on reefs. With distance north the unconsolidated sediment includes an increasing component of quartz sand from erosion of sand banks, dunes and the Tamala Limestone. Some quartz and heavy mineral sands are derived from terrestrial sources and transported from the Northampton Complex to the coast intermittently by streams discharging onto the coast.

Sediment movement in the micro-tidal environment is affected by prevailing SW swell and seas driven by the major weather systems, particularly by strong sea breezes. Sandy sediments form the active sand lens of the shoreface, the area in which waves move sediment, extends in a thickening wedge from its seaward limit in waters over 30m deep to the frontal dunes along the landward margin of the beach. There it abuts a rocky coast or, more commonly, merges with the dunes to form a barrier, a ridge of dunes, between marine and terrestrial processes.

Table 3-1: Sediment Sources and Sinks (After: Bowen & Inman 1966; van Rijn 1998)

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

3.3. MAJOR LANDFORM ASSOCIATIONS

At all scales the structure and formation of landforms is tied to the geology of the inner continental shelf, nearshore reef systems mainly of the southern part of the Mid-West coast and rock outcrops of coastal limestone at the shoreline. The bedrock outcrops of the nearshore waters and coast comprise a geologic framework consisting of a series of Pleistocene limestone features of marine and terrestrial origin which outcrop as islands, approximately shore-parallel reefs, rock platforms and cliffs. A delineation of the coastal landforms broadly follows the inshore and nearshore geologic framework of the primary compartments, with a further division at Dongara (Table 2-1; Figure 1-3; Figure 1-4 ; bathymetry shown in Figure 1-1; following approach by Searle & Semeniuk 1985). Each primary compartment experiences different metocean forcing at a regional scale due to the inner shelf influence and at a local scale through further modification to processes by the varied nearshore and inshore geologic structure.

The alongshore variability of the shelf and reef structure of the Mid-West coast is summarised at a primary compartment scale in Table 3-2, described in further detail per cell in Appendix D and classified in the vulnerability assessment in Section 5. It is demonstrated visually in Figure 1-1 and in the Department of Transport and Australian Navy Navigation Charts, Geoscience Australia bathymetry and survey records.

The Mid-West is a transition zone physically and climatologically. The region spans the shallow reefs and inshore lagoons that are common south of Dongara and the deeper shoreface north of Glenfield. Additionally, streams and rivers are increasingly common to the north of the Study Area, with the Irwin River at Dongara, Chapman River at Geraldton, and several small streams between there and the Murchison River at Kalbarri. Despite the presence of the streams, which have wave dominated mouths (Wright 1985; Digby *et al.* 1998; Perillo 1995) the northern sector of the Study Area is apparently sediment deficient. The largest unconsolidated sedimentary landforms – cuspate forelands and high barriers - are predominantly located along the southern shores. Conversely, extensive erosional forms, such as large cliffs and lagoons landward of exposed platforms are more prevalent in the northern sector.

Table 3-2: Structure of the Inner Shelf, Nearshore Reefs and Rock Outcrops of the Primary Compartments

Boundaries	General reef structure
Broken Anchor Bay to Murchison River mouth	Characterised by an inner shelf that narrows with distance north for depths <50m, negligible nearshore reef influence and extensive outcrops of coastal limestone at the shoreline, including a shore parallel reef that is the present shoreline in certain locations and cliffs.
Glenfield to Broken Anchor Bay	Characterised by a 100km and shallow inner shelf including the Houtman Abrolhos, 0.5-3km nearshore reefs of depths <10m and extensive outcrops of coastal limestone at the shoreline (including cliffs)
North Head to Glenfield	Dongara to Glenfield Characterised by a 60km wide inner shelf, with 30km width of depths <50m, limited influence of nearshore reef from 10-20m depth with narrow reef <10m depth, and extensive outcrops of coastal limestone at the shoreline.
	North Head to Dongara Characterised by a narrow inner shelf (20-50km wide), strong nearshore reef influence and extensive outcrops of coastal limestone at the shoreline.

3.3.1. Nearshore Morphology: Reefs and Sand Banks

The influence of changing metocean conditions on coastal sheltering provides an over-riding control on coastal landform change. Hence, the influence of reef structure on inshore metocean processes is included in the assessment of vulnerability through the *Nearshore Morphology* category for Susceptibility and *Inshore Substrate* category for Instability (Table 2-6). *Nearshore Morphology* classes the highest susceptibility rate for coastlines without reef and the lowest susceptibility for a continuous reef and lagoon. The three rankings in between incorporate concepts of varying reef continuity and structure (Figure 3-3). *Inshore Substrate* classes the most unstable inshore areas as those without any rock outcropping and the most stable as those with almost continuous rock cover or hard rock that has a high resistance to erosion (Figure 3-4).

The proximity of rock to the coast and its surface structure (width, depth, roughness and gaps) modify the local metocean processes in the lee of the reefs and islands (McNinch 2004; Silvester & Hsu 1993). Along the Mid-West coast water level, waves and currents interact with outcrops of coastal limestone to modify the inshore processes, including sediment transport and water circulation patterns (D'Adamo & Monty 1997). The coastal processes are discussed in Section 4.

Sediment availability and transport, and therefore the stability of the coast, is affected by the nature of the inshore substrate. Hence the morphology of the inshore substrate is included in the assessment of vulnerability largely through the *Inshore Substrate* category for Instability (Table 2-6). A hard rock substrate close to the surface of the seabed is unlikely to carry much available sediment for transport and is therefore the most stable. However, sediment is likely to be transported across such surfaces. Conversely bare sand surfaces are unstable and commonly show evidence of active transport, such as sand ripples.

3.3.2. The Shore: Shoreline Shape, Beaches and Rocky Coasts

The vulnerability of landforms along the shore, including the frontal dune complex (foredunes and frontal dunes) and barrier system, to changes in metocean forcing is dependent on sediment supply, shoreline configuration and orientation, beach type and presence of rock (Table 2-6). Their susceptibility is related to coastal aspect and shoreline configuration; and instability to the type of beach and frontal dune characteristics.

Coastal aspect, or the direction to seaward the coast faces, determines the prevailing and dominant metocean processes to which it is susceptible. In the present analysis coastal aspect is included in the assessment of vulnerability through the *Coastal Orientation* category for Susceptibility (Table 2-6). It is considered in relation to the exposure to major storms. *Coastal Orientation* has the highest susceptibility ranking for cells exposed to the west and lowest susceptibility for cells exposed to the south (Figure 3-3). However, this is a classification of the aspect of the majority of the sediment cell and neglects localised variability within a cell. Additionally, large shifts in aspect generally coincide with coastal compartment boundaries.

Susceptibility of the barrier and shoreline configuration increases with reduced geological control. This has been included in the assessment of vulnerability through the *Shoreline Configuration* and *Barrier* categories for Susceptibility (Table 2-6). Cuspate forelands and tombolos have the highest susceptibility of any shoreline configuration, followed by salients (Figure 3-3). Conversely, the least susceptible shoreline configuration is a straight, uninterrupted coast; however, this can be the most unstable. The vulnerability ranking for a cell may not account for the cuspate foreland or salient as these landforms are often located on the cell boundaries and do not represent the majority of the shoreline configuration within the cell. Each cuspate foreland or tombolo should be considered separately to the adjacent cells as it will often be more vulnerable to future environmental change.

Several different types of beach are recognised in the literature including sheltered and estuarine beaches (Nordstrom 1992; Jackson *et al.* 2002) and exposed, wave-dominated beaches (Wright & Short 1984; Short 2005). Beach stability has been included in the assessment of vulnerability through the *Beachface Morphology and Profile* category for Instability (Table 2-6). Instability rankings for these types have been ordered according to the degree of wave exposure, with the most unstable beaches exposed to the highest wave energy (Figure 3-4).

Perched beaches are common features of the Mid-West coast, as they are for much of the shore of the Swan Coastal Plain, but are not widely described in the literature (Green 2008; Doucette 2009). They are included in the assessment of vulnerability partly through the *Nearshore* and *Barrier* categories for Susceptibility and partly though the *Inshore Substrate* and *Frontal Dune* categories for Instability (Table 2-6). Susceptibility of the barrier and inshore increases with reduced geological control. However, perched beaches can occur on a smaller spatial scale than the sediment cell and should be considered in any local assessment.

3.3.3. Onshore Landforms: Barriers, Dunes and Rivers

Formation of a barrier is a response to large-scale, long-term processes associated with changes in sea level sweeping the inner continental shelf during a rise in sea level over the Holocene, the past 6 to 8,000 years. The response is continuing at present. Rogers (1996) recognised three phases of barrier development from the Mid-West coast of WA and this may be similar for the Mid-West coast. The phases are likely to be related to inter-decadal fluctuations in storminess, sea level and the wave regime, as well as pulsational sediment supply along the coast as well as an intermittent supply from the rivers. Such low-frequency changes are difficult to determine from the comparatively short, available historical records of coastal change although they may be apparent in the stratigraphic record.

Processes underlying barrier formation and the diversity of landforms associated with them have been widely discussed; for example see reviews by Roy *et al.* (1994), Hesp & Short (1999a) and Masetti *et al.* (2008). In a seaward sequence the main barrier features match those of a retrograding coastal sand barrier comprising active and inactive parabolic dunes and/or foredune ridges as well as the beach and shoreface as described by Cowell & Thom (1994) and Hesp & Short (1999a). The barrier systems of the Study Area include extensive episodic transgressive dune fields with active parabolic dunes and sand sheets between Cliff Head and Leander Point (Cells 18 to 20) and from Broken Anchor Bay to Bluff Point (Cells 54 to 62) that form major onshore sediment sinks in their respective compartments. The reach of coast between Nine Mile Beach and Headbutts (Cells 25 to 27) is the active component of a more extensive barrier system extending northward to Cape Burney South. However, much of the barrier is perched on coastal limestone platforms. Smaller, more-localised episodic transgressive barriers with active dunes occur in discrete sediment cells. These include the dune fields between Coolimba and South Illawong (Cells 14 & 15), Glenfield Beach and Coronation Beach (Cells 47 & 48), Bowes River and Whaleboat Cove (Cell 50) and from the Murchison River to Nunginjay Springs (Cell 64).

Other coastal land systems include foredunes plains that have developed landwards of calcarenite reef and islets as cuspate forelands and tombolos (Sanderson & Eliot 1996) or as narrow plains adjoining eroded dunes and infilling an embayment between headlands. The larger landforms include tombolos at Green Head, Point Louise, Leander Point and Point Moore; cuspate forelands at White Point, Eagles Nest and Shoal Point; and narrow foredune plains along sheltered sections of coast between Dongara North and Harleys Hole (Cell 22).

The susceptibility of barriers to change is a function of barrier type and size. Following the nomenclature of Roy *et al.* (1994), the largest and least susceptible to change are episodic transgressive barriers which have undergone phases of dune activity leading to development of a dune ridge through the formation of foredunes, blowouts and nested parabolic sand dunes as the ridge migrates landwards. The most susceptible to change due to metocean forcing are mainland barriers where a thin wedge of sand abuts rocky coast. However, there are differences between the Australian East and West Coasts. The principal distinction is that dunes forming the WA barriers commonly overlie the coastal limestone and therefore are comparatively less susceptible to change in the natural structure due to metocean forcing. Hence Roy *et al.* (1994)'s model is combined with the degree to which the barrier system is affected by the geological framework to determine its susceptibility to change through the

Barrier or Sand Body category for Susceptibility (Table 2-6; Figure 2-7). In the Study Area the least susceptible barriers are either large episodic transgressive barriers or barriers perched on high rock surfaces (Figure 2-7; Figure 3-3). The most susceptible to change are mainland beaches or unconsolidated spits and cheniers.

The stability of barriers and dunes is included through the *Frontal Dune Complex* and *Barrier Vegetation Cover* categories for Instability (Table 2-6; Figure 2-8; Figure 2-9). Under extreme onshore wind conditions barriers migrate landwards. The proportion of vegetation cover on the barrier, as a whole, is an indication of its surface stability. Similarly, vegetation cover on the foredunes and frontal dunes is also an indication of their stability. Additionally, scarping of the foredunes and frontal dunes is evidence of shoreline movement and possibly erosion. Hence, the degree to which a foredune is developed or the seaward margin of the frontal dune is cliffed provides an indication of the stability of the frontal dune complex (Figure 2-8; Figure 3-4).

Rivers are associated with mobile landforms and modify the supply of sediment to the coast, with rivers switching from being a sediment source during flood events, to potentially acting as sediment sinks for intervening periods. In general, the Mid-West rivers are small contributors of terrestrial sediment to the coast. The most unstable coasts are identified as those with barred river mouths in the *Beachface Morphology and Profile* category for Instability (Table 2-6). The nine rivers of the Mid-West Coast have barred mouths, often discharging to wave-dominated deltas, which may alternately trap or release sediment at the coast, with some mouth structures more susceptible. During significant runoff flooding, sediment may be released from the bar, beach and inshore areas in the path of the river flow. In addition sediment can also be supplied to the coastal system from the banks and bed of the alluvial channel, from flooded alluvial or estuarine flats and from the catchment. Within the Mid-West, a large proportion of the coarser sediment can be deposited offshore of the beach, with finer silts and clays dispersed across a wider area. After a scour event, the scoured channel and inshore area will act as a sink, trapping sediment until the bar has reformed, then becoming a feature that can be bypassed by alongshore sediment transport. While the bar is acting as a trap, it can potentially starve the downdrift coast until the bar is reformed and fully bypassing. The river mouths could potentially act as sediment sink for decades following a significant flood event.

3.3.4. Ranking Susceptibility and Instability for Different Beach Zones

The ranked likelihood of susceptibility instability for the nearshore, beachface, frontal dune complex and backshore zones are illustrated for barrier systems on a mixed sandy and rocky coast (Figure 3-3 & Figure 3-4).

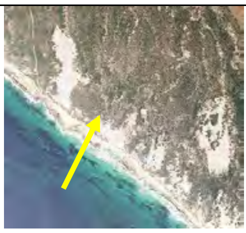
LAND SYSTEM	SUSCEPTIBILITY TO CHANGE		
Component	**Low**	**Moderate**	**High**
Nearshore Topography			
	Continuous offshore reef OR Shallow lagoon, rock platform or sand bank	Shallow intermittent reef OR Broken pavement (Depth <10m).	Unconsolidated sediments in bare sand OR Seagrass banks
Shoreline Configuration			
	Straight or seawardly convex rocky coast OR Made beaches	Arcuate or zeta form, deeply indented	Cuspate forelands and tombolos
Coastal Orientation			
	Coast faces southerly quadrant (SSE to SSW) and is subject to prevailing swell and sea breezes	Coast faces northerly quadrant (NNW to NNE) and is subject to NW storms and refracted storm waves	Coast faces westerly quadrant (WSW to WNW) and is subject to dominant storms
Barrier Type and/or Sand Body			
	Episodic transgressive barrier OR Perched dunes on a supratidal or higher rock surface	Stationary barrier OR Tombolo	Mainland beach adjacent cliff OR Narrow spit or chenier

Figure 3-3: Landform Associations and their Susceptibility to Changing Metocean Conditions

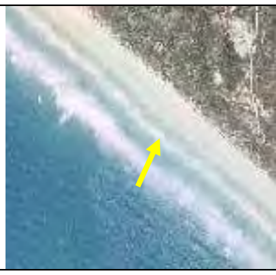
LANDFORM	RELATIVE INSTABILITY		
	Low	**Moderate**	**High**
Inshore Substrate			
	A high proportion (>75%) of shallow reef OR Pavement outcrops close to shore	Moderate (25 to 50%) proportion of reef OR Pavement near shore	Bare sand in water depths less than 5m close to shore
Beachface and/or Profile			
	Narrow, sheltered beach with a planar (flat) OR Segmented profile	Exposed beach with a wide berm and steep, reflective profile	Exposed, dissipative beach with multiple lines of breakers and rip currents
Frontal Dune Complex			
	A continuous, well-vegetated foredune ridge is located along the backshore of the beach.	The foredune ridge is discontinuous and comprised of a series of dune hummocks.	The foredune is absent and cliffing of the frontal dune is apparent along the beach backshore
Barrier Vegetation Cover			
	Broad, well-vegetated barrier in the lee of offshore structures and shallow inshore reefs	Moderately-wide and high dune field. Unknown depth to the limestone basement away from headlands	Narrow barrier with active dunes and/or sparse vegetation cover. Unknown depth to the limestone basement

Figure 3-4: Landform Associations and their Relative Instability

4. Coastal Processes

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

Coastal processes are active over all time scales simultaneously. Care is required to ensure the process of change is not inappropriately identified due to confined use of one or two concepts of change (refer to Section 4.4). Hence the hierarchy of geomorphic features, from landscape elements to mega-landforms and based upon spatial and temporal variability (Figure 2-6) has been used as an aid to identify active processes likely to determine the stability of the Mid-West coast.

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

- Meteorologic conditions contributing to the wind, wave and nearshore current regimes have been considered from stations at Jurien Bay, Geraldton and Kalbarri (Table 4-4). Particular reference is made to extreme weather events likely to generate storm surge or significant aeolian transport for dune formation;
- Tides and surges are described from water level records from Geraldton (Table 4-5);
- Descriptions of offshore wave conditions have been derived from waverider buoys off Jurien Bay and Geraldton (Table 4-8). Further information on the nearshore and inshore wave climate at Port Dension, Geraldton, Oakajee and Kalbarri has been compiled from prior studies. Further information on the transformation of waves across reef systems in included for Ledge Point (south of the Study Area; Eliot *et al.* 2012a);
- The influence of the river systems of the area on the coast is described using discharge datasets for the Irwin, Greenough, Chapman, Hutt and Murchison Rivers (Table 4-10). Further information is included using rainfall datasets for the two larger Greenough and Murchison Rivers.

The specific information used has been detailed in each section.

4.1. IDENTIFYING KEY METOCEAN PROCESSES

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

The National Committee on Coastal and Ocean Engineering (NCCOE 2004) has suggested climate change assessment should be undertaken using a sensitivity framework to reduce the likelihood that poorly understood or modelled processes are neglected (NCCOE 2004;

Abuodha & Woodroffe 2006). The framework suggests examining the sensitivity of the existing system to a suite of possible mechanisms, listed according to environmental (K1-K6) and process (S1-S13) variables (Table 4-1). By identifying the processes which are large amplitude or frequent, and to which the local system is most responsive, the focus for management may be highlighted.

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

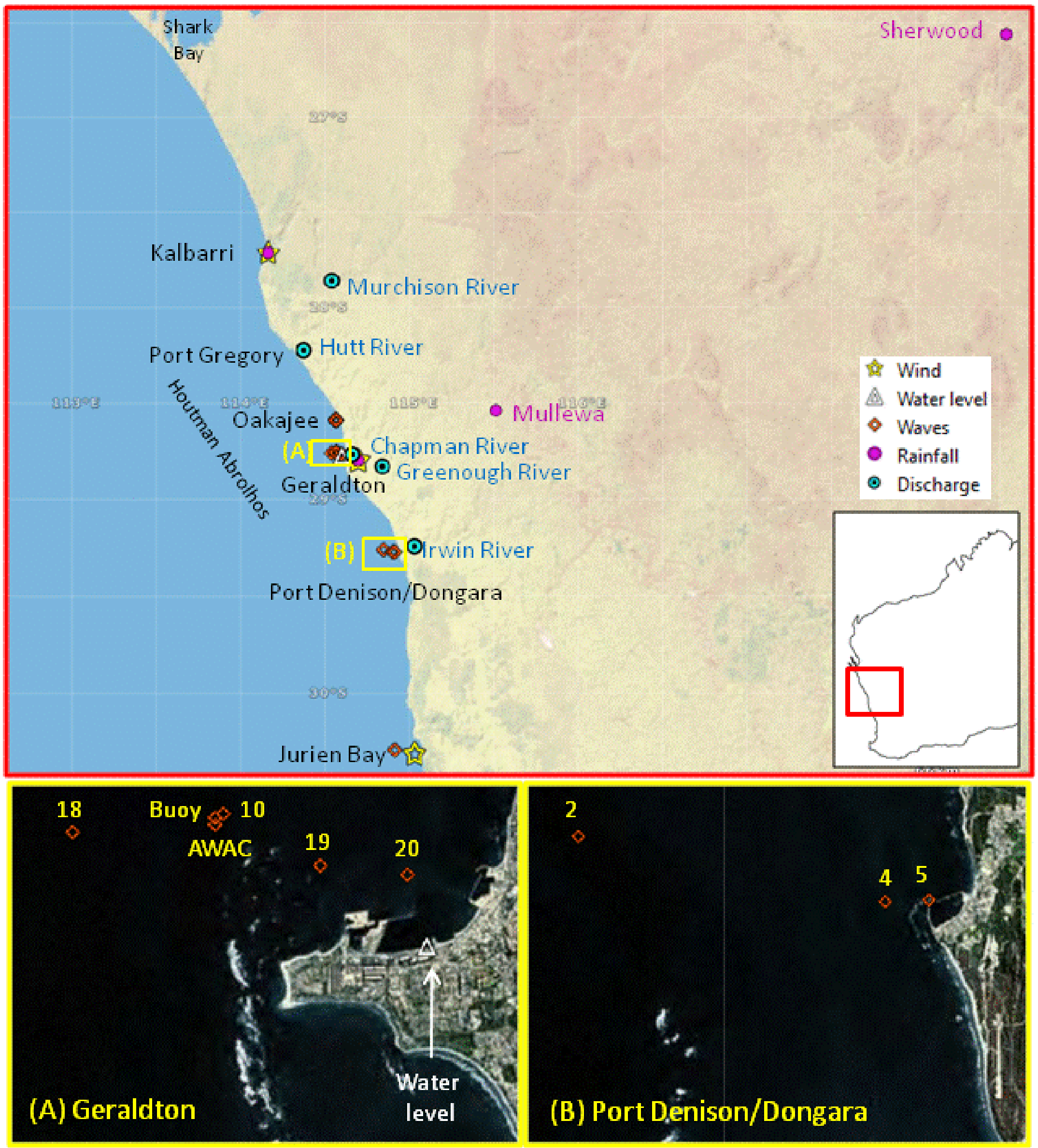


Figure 4-1: Monitoring Stations
Insets (A) Geraldton Waves and (B) Port Denison Waves
(Image Source: esri World Physical Map and USGS Aerials)

Within the Mid-West coast, the structure and formation of landform units (beaches, dunes and coastal barriers) are strongly tied to the presence and formation of nearshore reef systems, rock outcrops at the shoreline and the topography of the inner continental shelf. The inner shelf topography (defined here to 130m depth at the primary compartment boundary) has influenced the formation of the coast over geologic timescales and provides present sheltering to metocean processes. The primary compartments of the Mid-West are bounded offshore by a semi-continuous chain of limestone reefs, some of which outcrop as Islands, such as the Houtman Abrolhos (Figure 1-1; Table 3-2). Specifically, the presence or absence of such reefs provides wave sheltering or exposure that controls the development of cuspate forelands, tombolos and embayments (Sanderson & Eliot 1996).

The over-riding control on coastal landform change is the influence of coastal sheltering combined with changing environmental conditions (Box 4-1), and therefore an assessment of nearshore reef structure has been applied as a primary indicator of coastal sensitivity.

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

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

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

For this study, the relative importance of different processes has been considered with respect to the landform units described in Section 2.3. In general terms, there is a progression in time scales from rapid response at the beach scale, through to gradual, slow change for the barrier system as a whole (de Vriend *et al*. 1993; Cowell & Thom 1994).

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

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

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

The inner shelf structure, nearshore reef and islands systems and the underlying coastal limestone geology influence the Mid-West coastal processes.

The inner shelf structure can reduce some of the incident wave energy, largely as a result of refraction, with some influence of wave breaking and diffraction across the Houtman Abrolhos. The main delineation in the inner shelf structure is identifiable at the primary compartment scale, with the two more exposed compartments (Dongara to Glenfield and Broken Anchor Bay to Murchison River mouth) having a narrower and deeper inner shelf.

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

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

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

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

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

The frequency of coastal flooding, tidal cycles, inter-annual sea level fluctuations and vertical land movements must be considered when evaluating relative change in sea level. Increases in mean sea level due to El Nino / La Nina phase, plus a 19-year tidal cycle, have caused a dramatic increase in the number of coastal flooding events over the period 1993 to 2003. These are not directly related to Greenhouse-induced climate change (Pattiaratchi & Eliot 2008; Eliot 2011).

4.2. REGIONAL SCALE

The Mid-West coast is located approximately between latitudes 26° 50' S and 30° 14'S on the west-facing coast of Australia. It experiences a variable, sometimes high-energy wave climate as modelled offshore (Richardson *et al.* 2005). 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. Prevailing swell is south to southwest, generated from mid-latitude synoptic systems, with enhanced west to northwest activity during winter months. The incidence of swell and locally generated waves varies across the four primary compartments due to inner shelf structure and reef influence (Table 3-2).

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).

4.2.1. Meteorology

The Mid-West coast region, including Geraldton and Kalbarri, experiences a Mediterranean climate in the south and subtropical Mediterranean climate in the north (Gentilli 1971, 1972), with mild wet winters and hot, dry summers, interspersed with the influence of tropical cyclones. A regional summary of the climate in the Gascoyne-Murchison is provided in Bureau of Meteorology (1998).

The region lies within the northern half of the extra-tropical ridge and is dominated in summer by eastward travelling high pressure systems, within 26°S to 45°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 with central pressures from latitudes 35°S to 50°S to increase, through fronts or more direct synoptic winds systems. During summer, there is a southward migration of the convergence of the trade and monsoon winds resulting in tropical lows and occasional tropical cyclones (BoM 1998). The influence of tropical systems is rare, although it may be significant, as amply illustrated by the impact of TC Alby in April 1978 and the 'storm of the century' in 1956 (Henfrey 1968), and the generation of terrestrial flooding as illustrated by TC Clare in January 2006.

Climate summaries from the Bureau of Meteorology for Jurien, Geraldton and Kalbarri describe the seasonal ambient variations (Figure 4-2; station information in Figure 4-1 and Table 4-4). 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 to south-southwesterly sea breezes commencing around noon and weakening during the night. The sea breeze formation is similar to that reported for the Perth region (Pattiaratchi *et al.* 1997; Masselink & Pattiaratchi 1998): these southerly to south-southwesterly sea breezes blow almost sub-parallel to the northerly trend of the coastline; their onset is rapid, initial velocities are relatively high, and surface currents respond almost instantaneously. The sea breeze may occur in all seasons, although it is most frequent and intense during summer months.

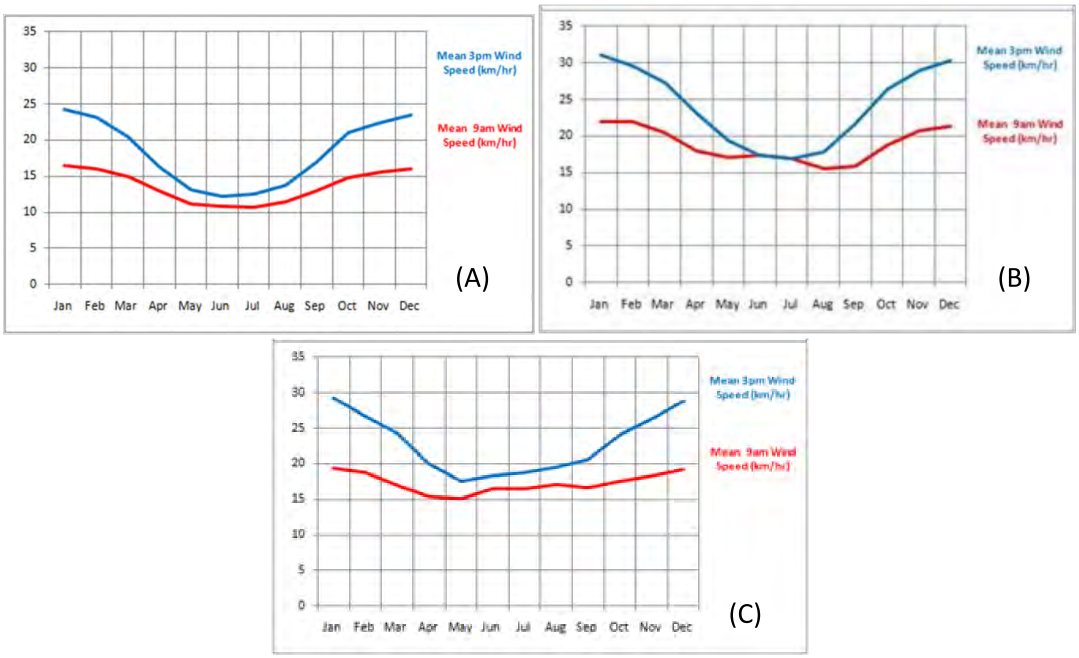


Figure 4-2: Mean Monthly 9am and 3pm Wind Speeds
(A) Kalbarri, (B) Geraldton and (C) Jurien
(Source: Bureau of Meteorology)

4.2.1.1. Weather systems

The average wind speed, direction, duration, extremes and event frequency for the major weather systems experienced on the Perth Metropolitan Coast have been summarised by Stul (2005) and are listed in Table 4-3. It is expected that these will be similar for the Mid-West coast, although with deviations in strength, direction and frequency of winds, particularly north of Geraldton. An example of this is the shift in the prevailing seabreeze wind direction from S at Jurien Bay and Geraldton to SSWly at Kalbarri; however, this is a potential artefact of topographic and geographic influences on meteorologic stations (Section 4.2.1.3). There is increased influence of dissipating tropical cyclones with distance north within the Study Area.

Table 4-3: Major Local Weather Systems

Weather System	Anticyclones	Squalls	Mid-latitude Depressions	Dissipating Tropical Cyclones	Sea Breezes
Occurrence	Annual	Dec – Apr	May – Oct	Jan– Mar	Oct – Mar (mainly)
Average Wind Speed	Light	15-20 m/s	15-29 m/s	Up to 40 m/s	10 m/s
Average Duration	Unknown	2-4 hours	10-55 hours	12-24 hours	~7 hours
Average Wind Direction	All	All	N to NW to W to SW	Depends on path	180-200^{o}
Frequency	3-10 days	13 days	3-8 / year	1 in 5 years	> 15 days/month
References	Gentilli 1972	Steedman 1982	Gentilli 1972; Steedman 1982	Damara WA 2008	Pattiaratchi *et al*. 1997

4.2.1.2. Storm events

Sustained high winds in the Mid-West coast region have similar synoptic origins to those experienced in the southwest. Consequently, the same nomenclature may be applied, (following Steedman & Associates 1982; Steedman & Craig 1983) which distinguishes between five sources:

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

Notably the last three sources of sustained high winds above are all caused by mid-latitude depressions, although the mechanism for wind generation is different, due to the relative dominance of radial geostrophic winds, pressure gradient intensification (generally longitudinal) and thermal gradients.

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, May 2003 and August 2005 (Coastal Engineering Solutions: CES 2005) and March 2011 (TC Bianca)

For the Mid-West coast region, sea breezes provide a significant baseline of moderate strength, but not extreme winds. Consequently, they are recognised to play a significant role in ambient coastal forcing (Pattiaratchi *et al.* 1997). The intensity and direction of the sea breeze is influenced by the shape and orientation of the coast, surface friction and synoptic pressure patterns, including the location of the approximately north-south aligned trough (Figure 4-3; Pattiaratchi *et al.* 1997; Bureau of Meteorology 1998). The summer sea breeze pattern may be suppressed when the trough is located offshore or during the influence of tropical systems.

Mid-latitude storm events are the most common source of extreme winds, generally occurring between May and September. A typical storm event is associated with an intense low pressure system location southwest of Australia, such that its clockwise rotation provides onshore winds (Figure 4-4). These storm systems commonly provide winds from the westerly half, often swinging from the northwest through to the southwest, with the peak winds speeds dependent upon the system location, path and thermal structure.

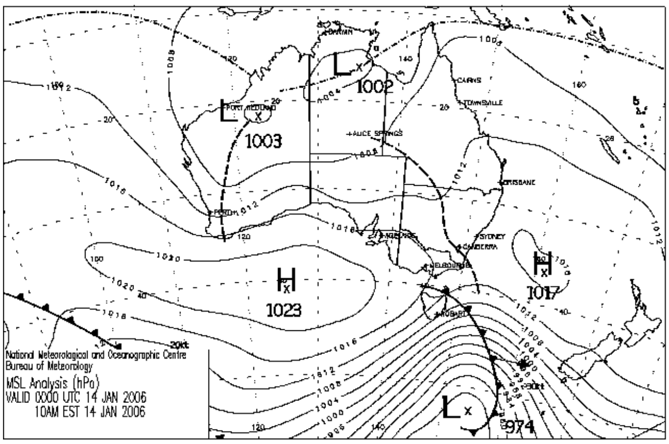


Figure 4-3: Common Summer Synoptic Conditions with Trough

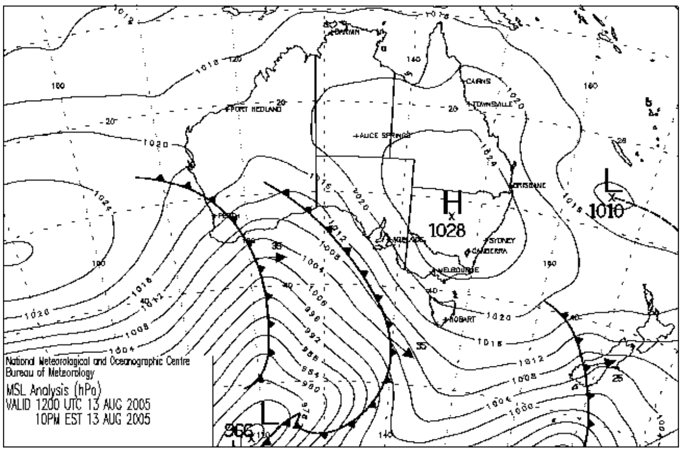


Figure 4-4: Common Winter Synoptic Conditions

Tropical cyclones affecting the Mid-West region are an infrequent phenomenon, but are significant, as they can cause extensive damage as a result of strong winds and flooding, caused by either heavy rainfall or ocean storm surges (Eliot & Pattiaratchi 2010). The intensity of tropical cyclones is such that direct impact, even by a relatively weak cyclone, commonly causes “highest recorded” levels of wind, wave height and water level (Damara WA 2008).

The tropical cyclone season affecting Western Australia occurs from November through to April with up to 10 tropical cyclones during one season (Damara WA 2008). Direct impact of cyclones along the Mid-West coast is less frequent occurring on average, once every five to ten years, with frequency increasing with distance north (Eliot & Pattiaratchi 2010).

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

Analysis of the tropical cyclone database has previously been undertaken by Damara WA, for the purpose of characterising cyclone climatology. Information presented here has previously largely been presented in Damara WA (2006, 2008). Different types of tropical cyclones will generate the highest surge, winds and waves or river flows in the Mid-West.

- The highest **surge** is associated with either tropical cyclones tracking parallel to the coast (shelf waves, eg. TC Bianca in 2011) or those which cross the coast to the south of the site (barometric surge, wind and wave set-up, eg. TC Glynis in 1970). (Damara WA 2006; Figure 4-5A). The relatively narrow shelf and west facing shore of the Mid-West reduce the significance of tropical cyclone induced surges compared to the North-West (Damara WA 2008);
- Tropical cyclones may produce strong **winds and waves** in any direction due to their intense radial structure, but most commonly are passing southwards offshore, and hence produce northeast winds, swinging through to northwest, westerly and southwest winds (Damara WA 2008); and
- High **river flows** are largely associated with tropical cyclones that recurve towards the southeast across the Pilbara causing heavy rainfall on the river catchments (eg. TC Vance in 1999; Figure 4-5B). The most significant flooding occurs once a catchment is already saturated, with sequential events such as TC Dianne and Carlos in 2011 generating widespread flooding (Figure 4-6). Note these two events did not recurve towards the southeast, but followed a track along the shelf.

4.2.1.3. Winds

Three long-term wind observation stations near to the Mid-West coast are at Jurien Bay, Geraldton and Kalbarri (Figure 4-1; Table 4-4). The longest set of observations is at Geraldton Port, since 1907, with automated recording of wind data only occurring from 1965 through the Bureau of Meteorology. The location of the Geraldton station moved inland to the airport from the port in 1953. The records contain a velocity scale change in 1960 at Geraldton with increasing directional accuracy in 1970 from 22.5° bands to the nearest degree.

Recorded winds are affected by geography, topography and instrument height, and need to be interpreted with these factors in mind. Of the stations considered here, Jurien Bay is within northwest facing dunes (1.6m), Geraldton is located 7.5km inland (33m) and Kalbarri is 1km inland on a northwest facing coast (6m), partially sheltered to the south by the landmass from Shoal Point to Red Bluff (Figure 1-1). Variation of median and strong wind speeds suggest that site location is significant with Kalbarri lower than the other two stations considered at Jurien Bay and Geraldton (Table 4-4). Maximum observed wind speeds do not show the same pattern, but this is typical for extreme conditions (Table 4-4).

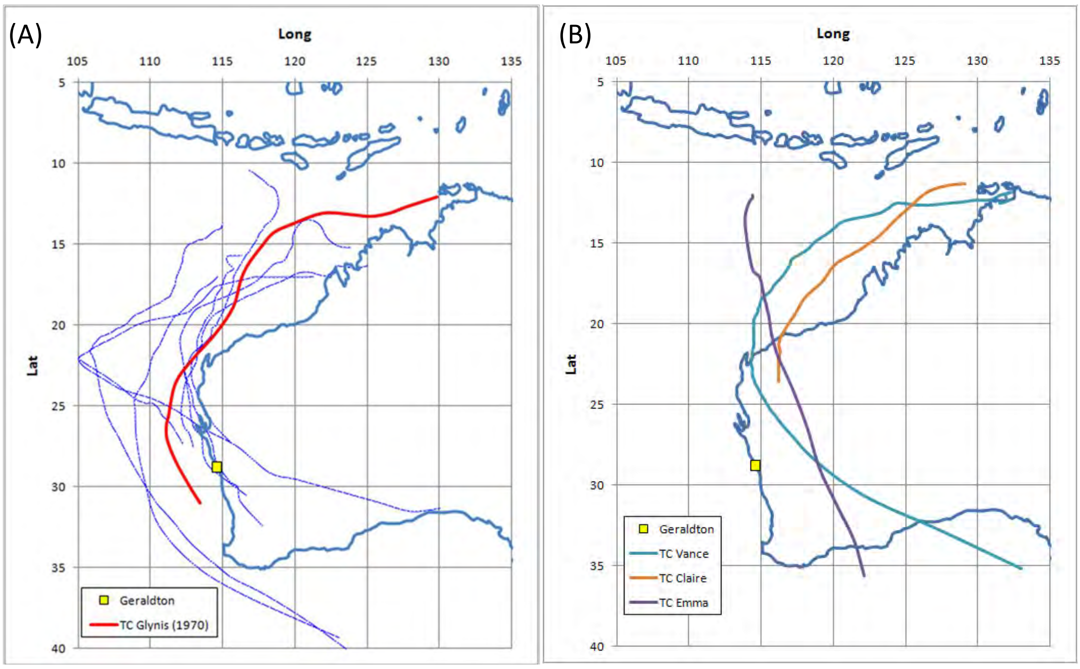


Figure 4-5: Tropical Cyclone Paths
(A) Causing Greatest Surge at Geraldton (1966 – 2008) and (B) Causing Some of the Recent Greatest Rainfall Events in the Mid-West
(Source: Damara WA 2008)

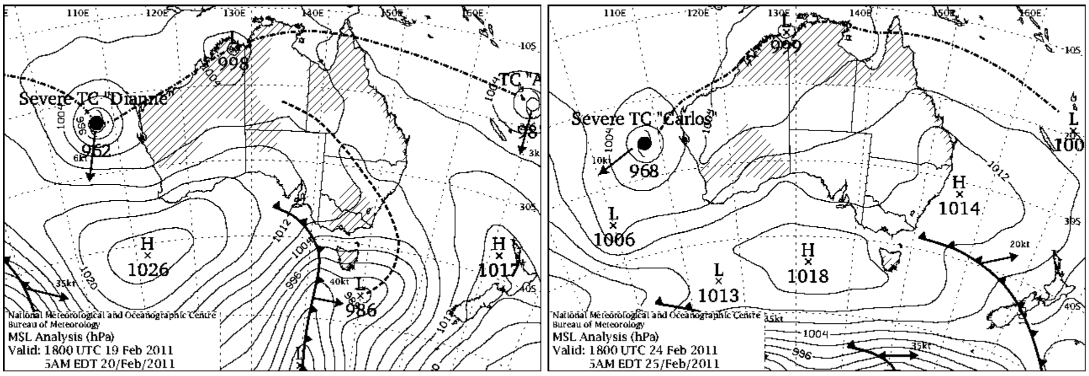


Figure 4-6: Tropical Cyclones Dianne and Carlos (2011) Causing River Flooding
(Source: Bureau of Meteorology)

The dominant wind directions of the two southern stations (Jurien Bay and Geraldton) are NE in the morning and S to SSW in the afternoon, the latter indicating the significance of sea breezes in the region (Figure 4-7B and C). At Kalbarri, the dominant wind directions are within the SE quadrant in the morning and from S to SW in the afternoon (Figure 4-7A). The 3pm wind speed distribution plots demonstrate an apparent shift in the prevailing sea breeze direction from S at Jurien Bay and Geraldton to SSW at Kalbarri (Figure 4-7). This could be an artefact of the station locations, with a shift inland at Geraldton and Kalbarri, compared to Jurien Bay, with Kalbarri sheltered from the south by the Bluff Point land. The long axes of the parabolic dunes and blowouts tend to be aligned S-N across the Study Area, with a slight shift to a SSE-NNW Eagles Nest to Bluff Point, indicating a southerly sea breeze with local topographic variations (Appendix C).

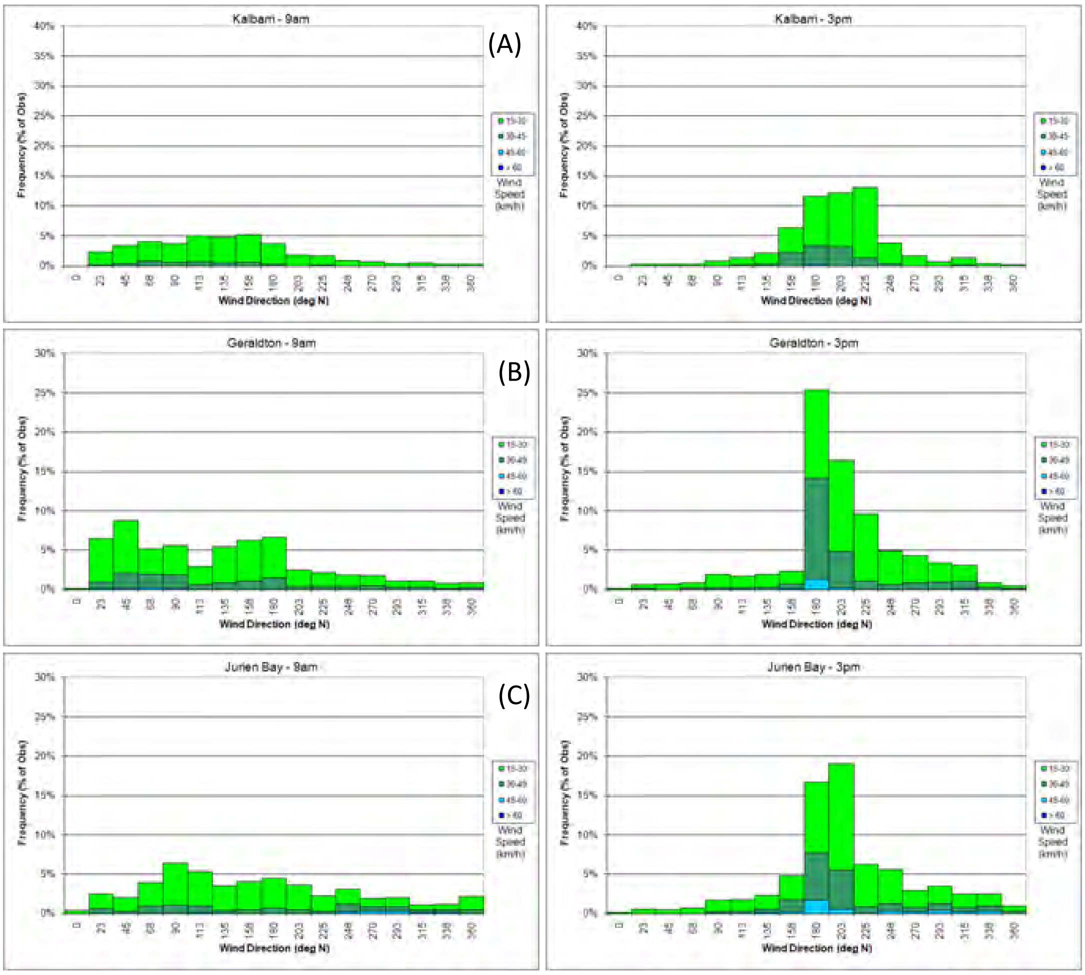


Figure 4-7: Wind Speed and Direction Frequencies for 9am and 3pm
(A) Kalbarri, (B) Geraldton and (C) Jurien Bay
(Source: Bureau of Meteorology)

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

Wind observations at Jurien Bay, Geraldton and Kalbarri over the period of record have shown considerable interannual variability, in keeping with assessments of storminess for the Perth metropolitan region (Steedman & Associates 1982; Panizza 1983). Annual summations of the 9am wind speed cardinal components (E-W and N-S) have been used to examine whether there are any apparent patterns of change or standout years (Figure 4-8). The 9am wind indicates the prevailing winds with limited influence of the seabreeze.

Table 4-4: Wind Observations for the Mid-West Coast (Source: Bureau of Meteorology) Note change in velocity scale in 1960 at Geraldton

Station	Location	Lat. (S)	Long. (E)	Height (m)	Dates	50% Wind (km/hr)	90% Wind (km/hr)	Max Obs. (km/hr)
8251	Kalbarri	27.712°	114.165°	6	1970-2010	13.0	27.7	126.0
8051	Geraldton Airport	28.795°	114.698°	33	1941-2010	16.6	33.5	101.9
8050	Geraldton Port (not included herein)	N/A	N/A	3	1907-1953	15.5	24.1	117.7
9131	Jurien Bay	30.308°	115.031°	1.6	1969-2010	14.8	33.5	140.8

Figure 4-8 shows the nett annual easterly and northerly drifts at Jurien Bay, Geraldton and Kalbarri stations. There are limited patterns of change apparent in the record. The inland Geraldton station didn't record the same variability in easterlies as Jurien Bay or Kalbarri, which showed some years with a stronger westerly component and weaker southerly components. Kalbarri had periods of stronger easterlies in the mid 1970s and mid 1990s, potentially attributed to a N-S shift in the sub-tropical ridge (BoM 1998). Jurien Bay demonstrated a period of stronger southerlies from the mid 1970s to mid 1990s. Winds at Geraldton have had an increased southerly dominance since the 1960s, not reflected in the Jurien Bay or Kalbarri records since the mid 1990s. Kalbarri had short periods of stronger southerly winds around 1980 and 1990, also recorded at Geraldton to a lesser magnitude.

4.2.2. Water Levels

The sustained water level measuring station for the Mid-West coast is at Geraldton (Figure 4-1; Table 4-5). This dataset has reliable recordings since 1966, after the Australia Height Datum was established from 1965 (Easton 1970; Wallace 1988), with a datum shift in 2005 (Damara WA 2008). The water level record is shown in Figure 4-9. The shorter 10 year dataset for Jurien Bay is not considered in detail, other than for a consideration of tidal planes.

Table 4-5: Water Level Observations for the Mid-West Coast (Source: Royal Australian Navy Hydrographic Office)

Station	Location	Lat. (S)	Long. (E)	Year Commenced
62290	Geraldton	28°47'	114°36'	1966

Key water level processes affecting the Mid-West coast include tides, atmospheric surges, resonant phenomena, seasonal and inter-annual mean sea level variations. The relatively narrow shelf and west facing shore of the Mid-West reduces the significance of both tides and tropical cyclone induced surges relative to the north-west (Damara WA 2008). An analysis of the range and standard deviations of hourly water levels at Geraldton has been included to describe the relative influence of tidal and non-tidal water level signals (National

Tidal Facility 2000; Eliot 2010). The water level time series was decomposed into approximations for mean sea level (30 day running mean), tide (Doodson-x_0 filter) and surge (residual), with some overlap between the approximations (Table 4-6).

Here the surge signal is likely to include resonant phenomena. The relative standard deviations indicate that tides are the major water level process, with mean sea level and surge providing a similar contribution. However, the relative ranges show a different pattern, with the non-tidal components having a larger ratio to tide, suggesting that they can intermittently overwhelm the tidal signal for the micro-tidal Mid-West coast.

Table 4-6: Mean Sea Level, Surge and Tide Approximations

	Geraldton (1966-2008)	
	Range	Standard deviation
Water Level (cm CD)	-28 to 180 (228)	24
Mean Sea Level (cm)	36 to 97 (61)	11
Surge (cm)	-35 to 50 (85)	10
Tide (cm)	-37 to 41 (78)	18

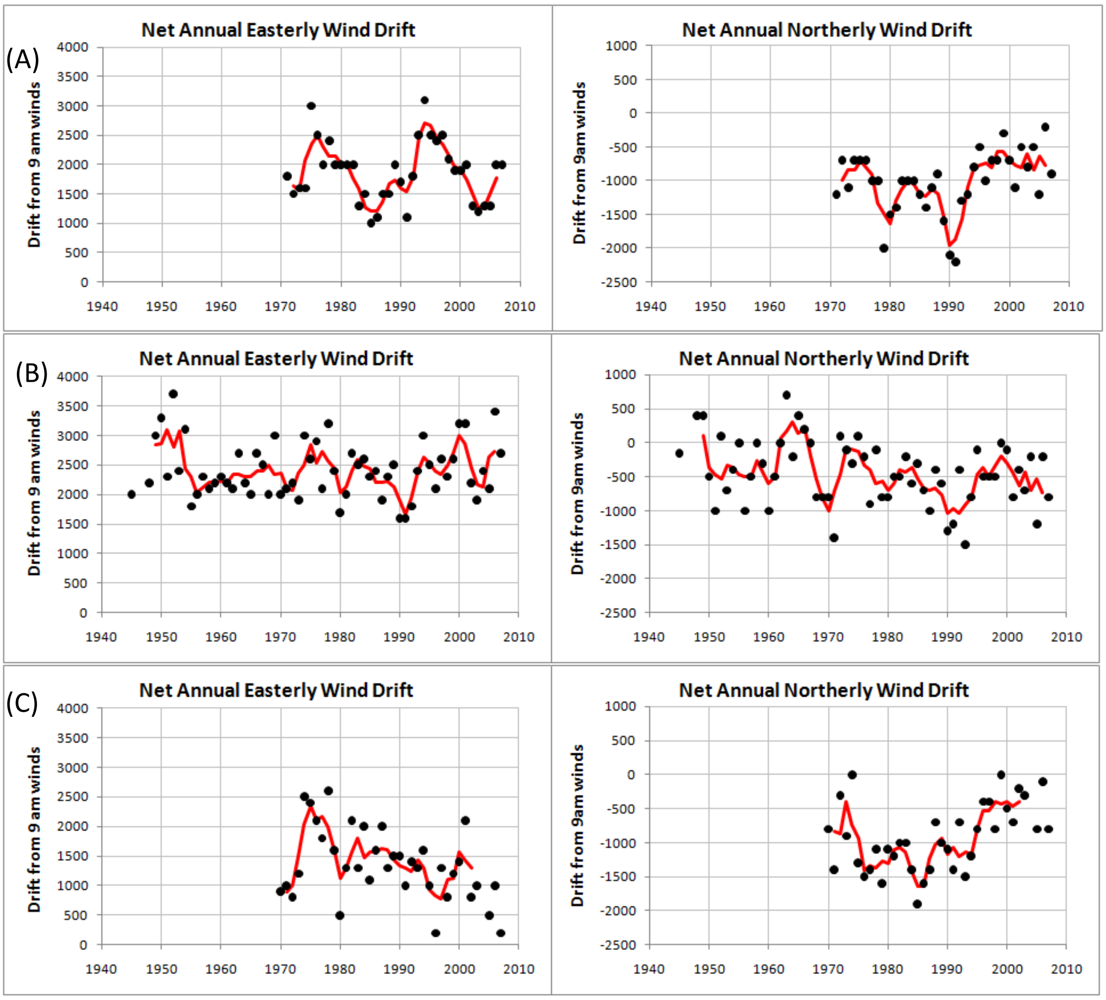


Figure 4-8: Annual Easterly and Northerly Wind Drift
(A) Kalbarri, (B) Geraldton and (C) Jurien Bay

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

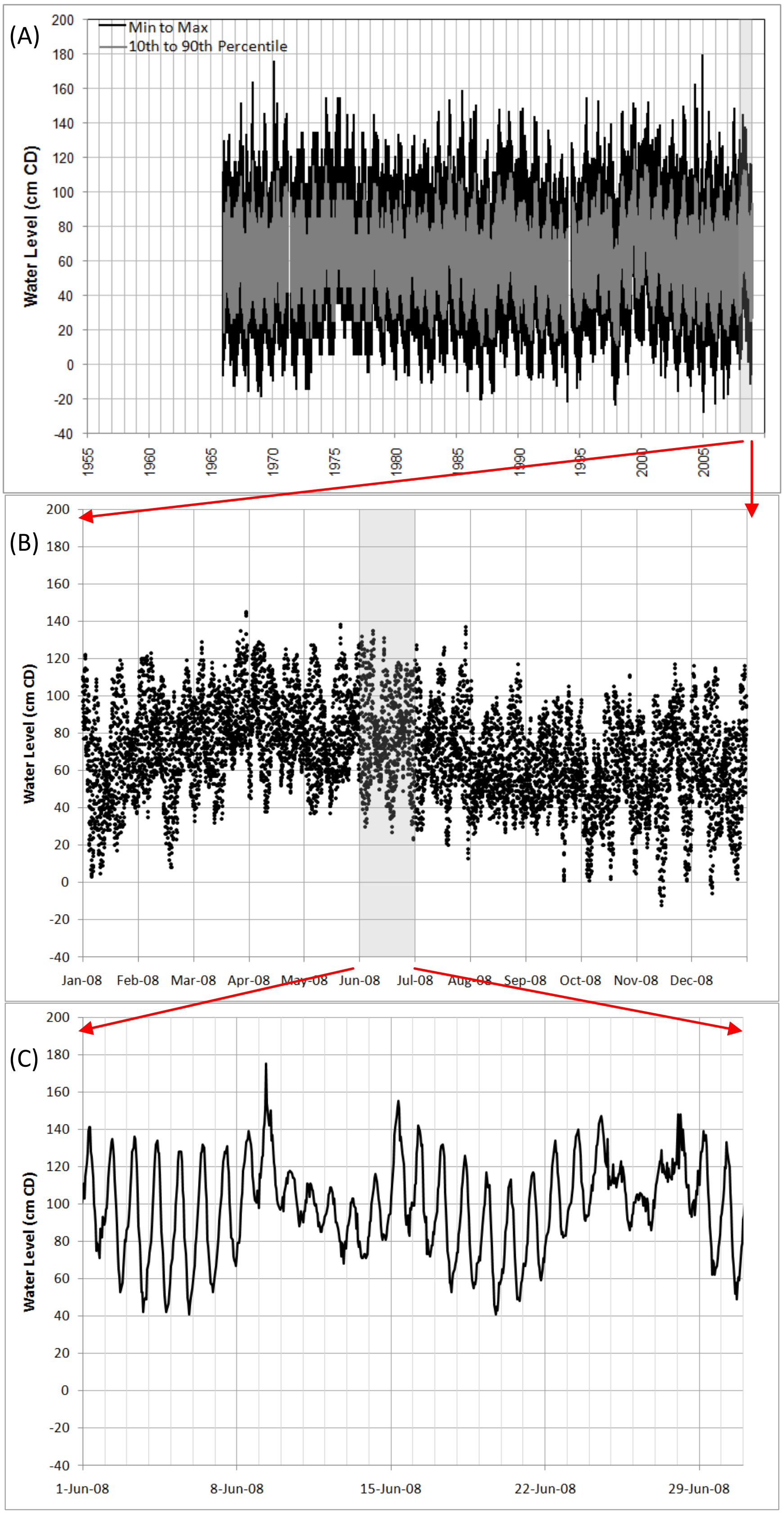


Figure 4-9: Water Levels (1966-2008) for Geraldton
(A) Total Record, (B) 2008 and (C) June 2008
(Source: Royal Australian Navy Hydrographic Office and Geraldton Port Authority)

4.2.2.1. *Tides*

Geraldton and Kalbarri are two of the Standard Ports defined by the Royal Australian Navy Hydrographic Office, with annual tidal predictions published in the Australian National Tide Tables (Department of Defence 2010). Jurien Bay and Port Gregory are secondary ports within and adjacent to the Study Area, with tidal levels derived from harmonic constituents. The mainly diurnal tides are microtidal with a tidal range of range of 1.1-1.2 m from LAT to HAT (Table 4-7).

Table 4-7: Tidal planes for Kalbarri, Port Gregory, Geraldton and Jurien Bay (Source: Department of Defence 2010)

Tidal Level		Water Level (mCD)			
		Kalbarri	Port Gregory	Geraldton	Jurien Bay
Highest Astronomical Tide	HAT	1.1	1.2	1.2	1.2
Mean Higher High Water	MHHW	0.7	1.0	1.0	0.8
Mean Lower High Water	MLHW	0.5	0.8	0.8	0.6
Mean Sea Level	MSL	0.5	0.6	0.6	0.5
Mean Higher Low Water	MHLW	0.4	0.4	0.4	0.5
Mean Lower Low Water	MLLW	0.3	0.3	0.2	0.3
Lowest Astronomical Tide	LAT	0.0	0.0	0.0	0.0

The tidal sequence is affected by monthly spring-neap cycles, bi-annual and inter-annual signals (Figure 4-9). The tidal range varies on a bi-annual cycle, with solstitial peaks in June and December. The tidal sequence is further modulated by the 8.85-year lunar perigee and 18.6-year lunar nodal cycles (Damara WA 2008; Eliot 2010). The lunar nodal cycle is dominant, with apparent peaks in 1987 and 2006, resulting in a 20% variation in maximum daily tide range between low and high years (Damara WA 2008). The seasonal range of water level is approximately 0.3m (Pariwono *et al.* 1986), mainly a non-tidal phenomenon, although commonly attributed to the S_a (solar annual) tidal constituent.

4.2.2.2. *Atmospheric Surges*

The contribution of surges to the water level record is high relative to the small tidal signal in the Mid-West coast area. The atmospheric surge can be of a similar order of magnitude to the tide at Fremantle, with similar trends expected in the Mid-West (Pattiaratchi & Eliot 2008). Dependence of water level upon weather conditions was also noted by Provis & Radok (1979) and suggests that the majority of surge is atmospheric in origin, a combination of barometric effect, wind and wave setup, related to mid-latitude storms. The track of the weather system will result in variation in surge levels across the region, as demonstrated by discrepancies in surge peaks between Geraldton and Fremantle (Eliot *et al.* 2012a). The peak in the extra-tropical surge occurs in June to July in Fremantle and May to June in Geraldton (Damara WA 2008). Surges may also occur due to more unusual meteorological events, such as Tropical Cyclone Glynis in 1970, and are often combined with resonant phenomena, such as shelf waves. High surge conditions may induce substantial, albeit commonly short-lived, beach responses.

4.2.2.3. Resonant Phenomena

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

Resonant phenomena play a significant role in the persistence of water level variations after an environmental perturbation (Rabinovich 2008). Resonance within the Mid-West region, including seiching, has been specifically identified as a result of coastal lagoon structure (Allison & Grassia 1979; Petrusevics *et al.* 1979). Forcing mechanisms may include storm systems, pressure jumps or thunderstorms, the latter of which are more common in summer than winter (Wijeratne *et al*. 2011).

Continental shelf waves, often remotely generated by tropical cyclones, can positively interact with atmospheric surge (Figure 4-10; Eliot & Pattiaratchi 2010). A continental shelf wave of 0.75m, generated by Tropical Cyclone Bianca, was recorded at Fremantle and Geraldton in March 2011.

Tsunamis generated in the Indian Ocean can result in high water levels associated with the leading waves as well as local seiches on the shelf, with the highest water level residual at Geraldton occurring during the 2004 Boxing Day Tsunami (Pattiaratchi & Eliot 2008).

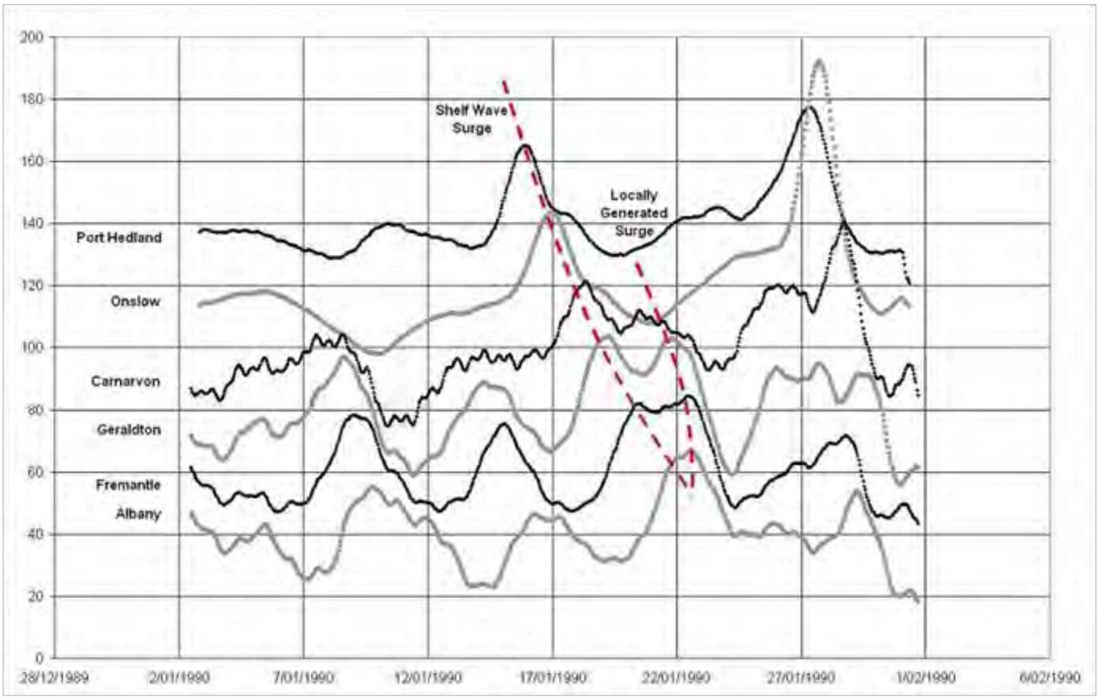


Figure 4-10: Shelf Wave Interaction with Locally Generated Surge

4.2.2.4. *Mean Sea Level Variations*

The 30-day and annual running means of water levels indicates two significant sources of slowly varying sea level fluctuations, at seasonal and inter-annual time scales (Figure 4-11). The long-term record for Geraldton (1966-2003) suggests a mean sea level rise of 0.5 mm/year, although the trend for any time period is strongly affected by inter-annual fluctuations, and therefore should be interpreted with caution (Damara WA 2008). Also, the tide gauge location in Geraldton was shifted in 1977, which may provide some uncertainty in the estimate of relative sea level rise.

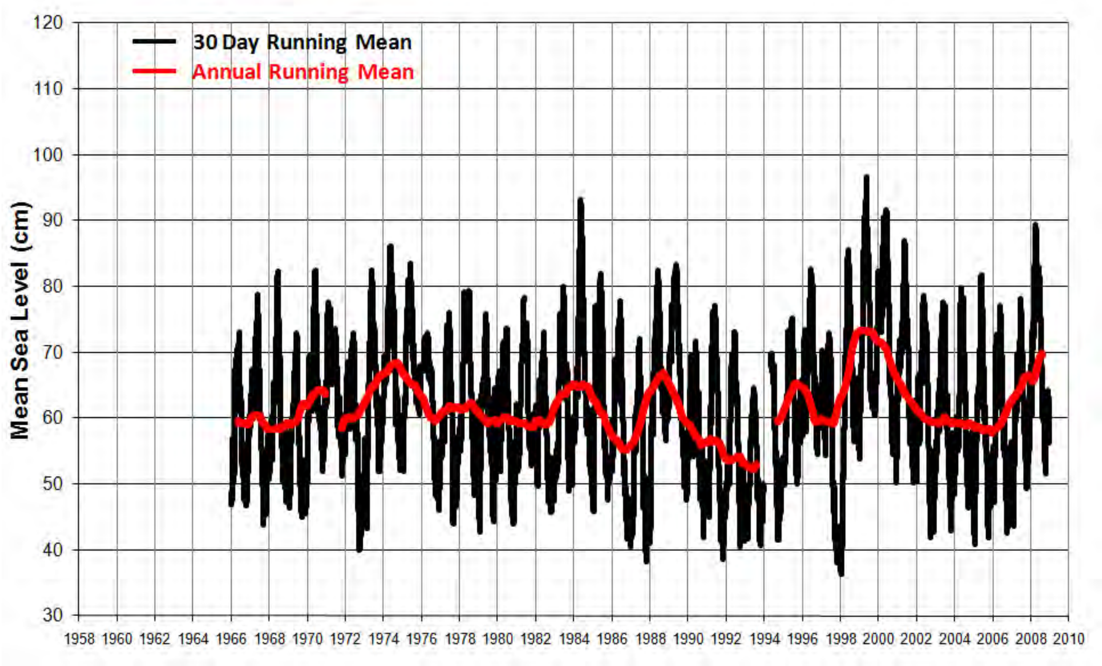


Figure 4-11: 30-Day and Annual Running Mean Sea Level for Geraldton (1966-2008)

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

The inter-annual relationship between mean sea level and climate fluctuations is suggested by a strong correlation between annual average water level and SOI - the Southern Oscillation Index (Pattiaratchi & Buchan 1991). The SOI is determined by the barometric pressure difference between Darwin and Hawaii, and has been demonstrated as a reasonable indicator of El Nino or La Nina climatic conditions. The sea level relationship to SOI indicated by Figure 4-12 occurs along the entire Western Australian coast (Pariwono *et al.* 1986; Pattiaratchi & Buchan 1991; Feng *et al.* 2004).

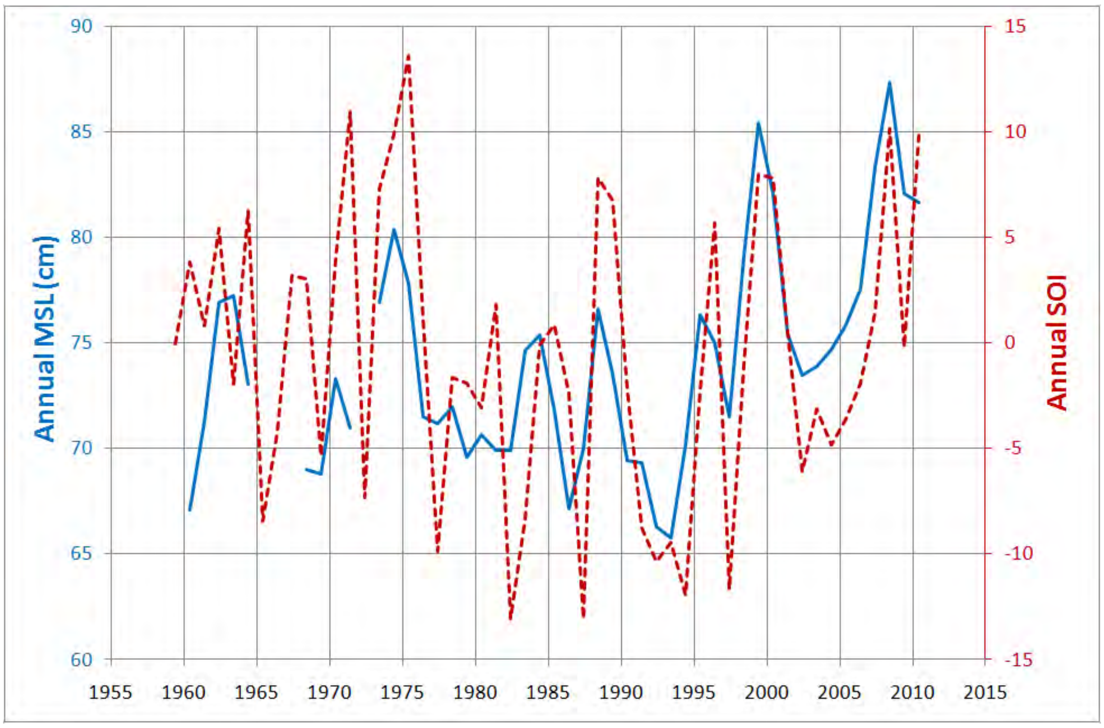


Figure 4-12: Correspondence between the Annual Means of Fremantle Mean Sea Level and SOI (1960 to 2010)

4.2.2.5. Extreme Water Levels

The relative timing of tide, mean water level and extra-tropical surge controls the potential for high water levels which occurs in May-June in Geraldton. The timing of high water levels in this region is generally out of phase with the tropical cyclone season. An exception is the high water level associated with TC Glynis (1970). The extreme water level distribution has excluded the 2004 Boxing Day Tsunami which generated a water level at Geraldton 0.9 m higher than TC Glynis.

Inter-annual cycles of tidal potential and mean sea level modify the likelihood of high or low water level events (Eliot 2011).

An inundation assessment at Geraldton in the 1980s used the 2.0m AHD (2.55m CD) contour to estimate the likely area of flooding from an approximate 1000 year Annual Recurrence Interval storm surge inundation event (PWD 1983b).

4.2.3. 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 were planned. From 1971 to 1994, these measurements were sporadic in nature, with comparatively short term deployments of one to four years.

From 1993, a series of permanent offshore waverider buoy installations have been progressively undertaken to provide a regional description of the wave climate throughout the southwest. The two buoys most relevant to the Mid-West coast are those at Jurien Bay (south of the Study Area) and Geraldton since 1999 and 1998 respectively (Figure 4-1; Table 4-8). The Jurien Bay buoy was upgraded to a directional buoys in 2009. The Geraldton waverider buoy was removed in 2006, with an AWAC meter used since 2005 in a location 7.5km south of the waverider (Grant Ryan *pers. comm.*). Observations from the wave rider buoys off Geraldton Harbour and at Jurien Bay are illustrated in Figure 4-13 and Figure 4-14.

Wave conditions are strongly modulated by water levels due to depth limited wave breaking and influence of refraction across the inner shelf. Shorter inshore records of non-directional wave data are included for investigation of reef influence on inshore waves at (locations in Figure 4-1 and Table 4-8 with results discussed in Section 4.3.3):

- Ledge Point (south of Study Area) in 2004-2006 for reef influence on inshore waves;
- Port Denison from 1974-1976 prior to the harbour construction in 1979 (PWD 1976);
- Geraldton in the 1980s at four locations, largely for consideration of Port and navigation channel dredging requirements (Steedman Limited 1985; DMH 1988);
- Oakajee for port design and model calibration in 1998-2000 (non-directional for Department for Planning and Infrastructure, 2006-2007 and 2007-2008 (both directional datasets collected for Oakajee Port & Rail by RPS Metocean Engineers) Datasets summarised in Damara WA (2009); and
- A short period of wave measurements was collected at Whitecarra Creek, circa 1995, for determining littoral drift rates (Oceanica 2010.).

This study neglected the short deployments adjacent to the Jurien Bay Boat Harbour in 1981 to 1982 (PWD 1984); at Geraldton prior to 1981 (Locations 6 and 10; Department of Transport website and described in Steedman & Associates 1983a); at Oakajee in 1980, 1982-1983, 1997, 1997-1999 and 2000 (Steedman & Associates 1981; Steedman & Associates 1983b; WNI Science & Engineering 1999; WNI Oceanographers and Meteorologists 2001; Metocean Engineers 2006); and offshore of Point Moore in 1990 (Steedman Science & Engineering 1991) as they were not compared to any measured offshore datasets or the data were not previously compared in the literature. The Department of Transport is the custodian of these datasets.
Spatial variation of the wave climate is suggested by wave modelling from 1997 to 2004 (Figure 4-15; Richardson *et al.* 2005). This shows a major variation in wave height occurring across the inner shelf in depths less than 50m, corresponding to the varied structure of the inner shelf of the primary compartments, including the influence of the Houtman Abrolhos. There is a general decrease in wave heights towards shore due to depth effects, along with increasing shelter from reefs and islands (Table 4-9). This cross-shelf variation in wave climate limits direct comparison of waverider buoy observations, as these are generally obtained from sites on the shelf (Figure 4-1; Table 4-8). Measurements from Geraldton are significantly damped due to the shallow depth of observation (12m) and the shelter provided by the Houtman Abrolhos. Jurien (42m) is likely to provide a closer representation to offshore wave conditions for the Study Area south of Geraldton with the Geraldton buoy (12m), providing limited representation of waves at depths of ≈10m between Geraldton and Whale Boat Cove (in the lee of the Houtman Abrolhos).

Table 4-8: Wave Observations Incorporated for the Mid-West Coast (Source: DoT; PWD 1976; Steedman & Associates 1983a; Steedman Limited 1985; DMH 1988; WNI Science & Engineering 1999; WNI Oceanographers & Meteorologists 2001; Metocean Engineers 2006; Damara WA 2009; Grant Ryan *pers comm.*)

Station	Location	Lat. (S)	Long. (E)	Depth (m)	Installed	Removed
12	Oakajee	28°35'28"	114°33'57"	15	12/3/1980	23/9/1981
42	Oakajee	28°35'26"	114°33'57"	18	3/6/1998	14/12/2000
	Oakajee (AWAC)	28°34'58"	114°33'53"	12	6/2006	1/2007
	Oakajee (AWAC)	28°35'22"	114°33'55"	20	11/2007	7/2008
	Geraldton – Channel	28°45'24"	114°33'56"	12	1/3/1999	31/12/2006
	Geraldton –AWAC Directional	28°45'28"	114°33'56"	13	1/3/2004 3/3/2005	15/8/2004 Current
18	Geraldton	28°45'32"	114°32'28"	27	30/12/1983	24/01/1985
10	Geraldton	28°45'22"	114°34'01"	12	13/03/1980	31/03/1987
20	Geraldton	28°45'55"	114°35'55"	6	30/12/1983	24/01/1985
19	Geraldton	28°45'30"	114°35'01"	10	30/12/1983	24/01/1985
2	Port Denison	29°15'43"	114°50'50"	20	29/7/1974 14/7/1975	11/12/1974 31/8/1975
4	Port Denison	29°16'22"	114°54'21"	14	15/7/1975	21/10/1976
5	Port Denison	29°16'21"	114°54'51"	8	29/10/1975 24/6/1976	13/12/1975 15/11/1976
40	Jurien Bay	30°17'30"	114°54'52"	42	27/10/1997	Current

The time series of observations for the two wave rider buoys is relatively consistent, albeit with significantly lower wave heights at Geraldton (Figure 4-13 to Figure 4-14).
The discrepancy of wave climate descriptions between sites may also 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 (Riedel & Trajer 1978; Li *et al.* 2009). Consequently, it is suggested that an extended period of record needs to be used when interpreting wave conditions. Recent wave modelling has been conducted at UWA to extend the wave record, using modelled information, from 1970 to 2009 across the south west (Bosserelle *et al.* In Press). The results could be used in future to compare the alongshore variation in the wave climate at the approximate depths of the offshore buoys (≈40m).

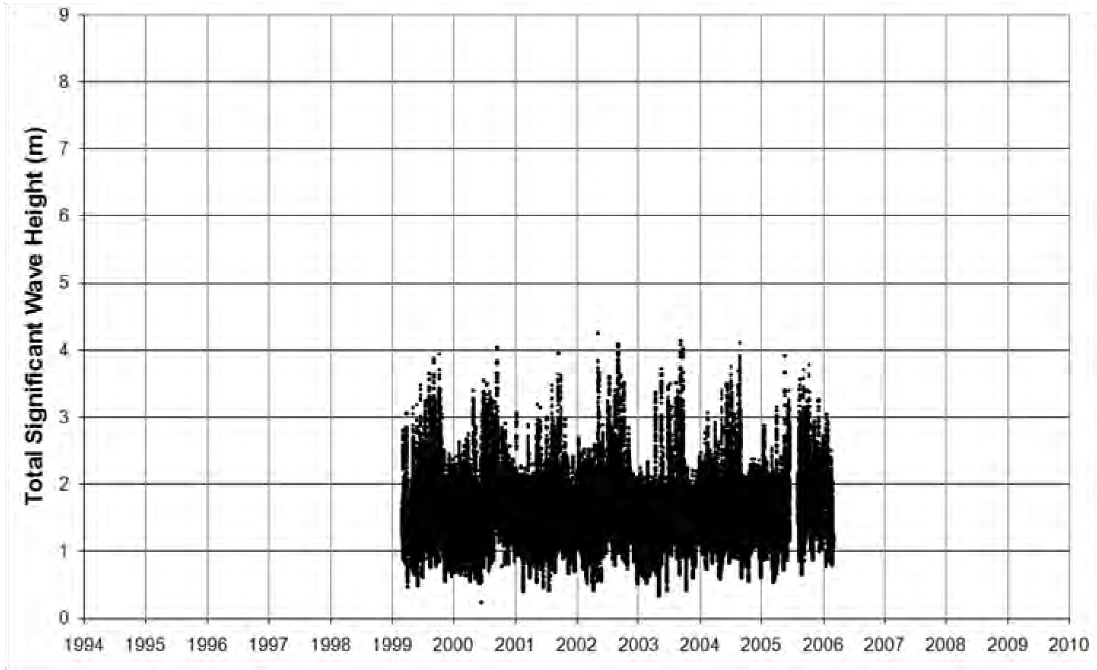


Figure 4-13: Geraldton Channel Buoy Wave Heights (1999-2006)
(Source: Geraldton Port Authority)

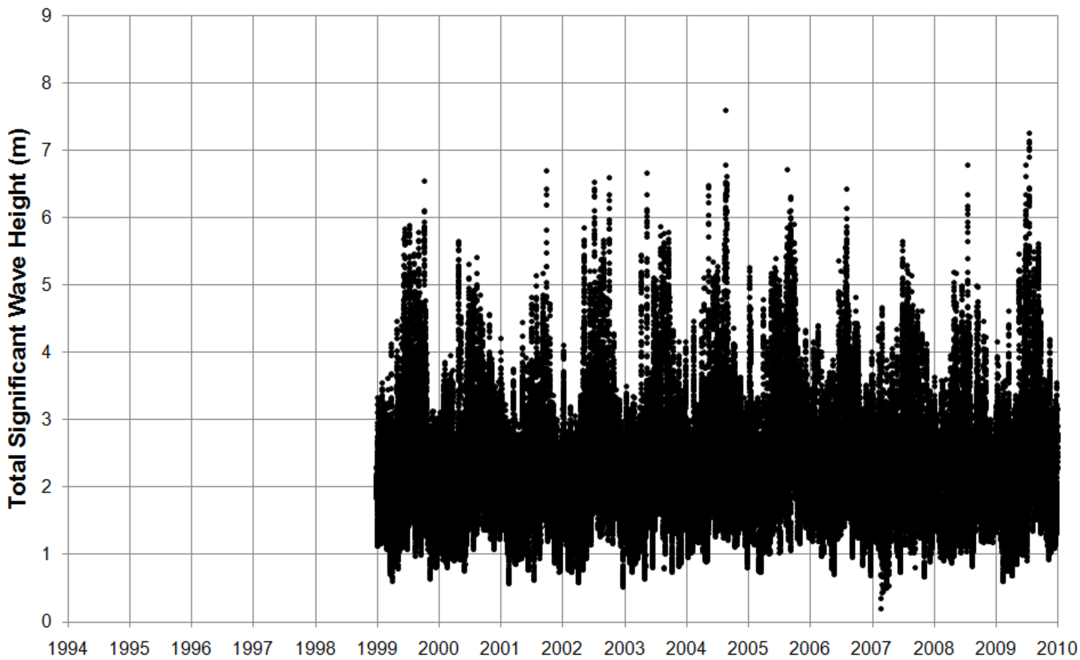


Figure 4-14: Jurien Offshore Wave Heights (1998-2009)
(Source: Department of Transport)

At Rottnest (south of the Study Area), analysis of the first three years of records from 1994 to 1996 showed an ambient wave climate of approximately 1.5 m significant wave height and 7 seconds (T_{01} statistic) during summer, increasing to approximately 2.0 m significant wave height and 9 seconds period during winter (Lemm 1996; Lemm *et al.* 1999; Rottnest buoy information summarised in Eliot *et al.* 2012a). The longer record from 1994 to 2009 shows high inter-annual variability of extreme waves, but the ambient summer-winter cycle remains relatively consistent from year to year (Li *et al.* 2009). The peak winter wave energy occurred in 1996 and the lowest recorded occurred in 2001. A similar trend is anticipated at Jurien Bay with greater discrepancies with distance north of Geraldton, related to changes in local weather patterns, change in shelf structure and proximity to storms.

Table 4-9: Median and 1% Significant Wave Heights

Location	Depth	Period	Median H_s (m)	1% H_s (m)
Geraldton	12m	March 1999 to December 2006	0.88	2.0
Jurien Bay	42m	January 1998 to December 2009	2.2	4.9

Plots of the joint distribution of significant wave height and peak wave period for the period of 1999 to 2006 for Jurien Bay and Geraldton demonstrate a similarity in the shorter period locally-generated waves, with the largest discrepancy between sites for the higher energy storm waves and longer period swell (Figure 4-16). This variation between sites is considered further using the directional wave record for 2006 only for Geraldton (Figure 4-17). The main observations for Geraldton are: there is a narrow band of directions where swell is observed at Geraldton due to refraction and a reduction in westerly swell by the Houtman Abrolhos (Figure 4-15); and smaller NW to N locally generated waves at Geraldton due to the Houtman Abrolhos.

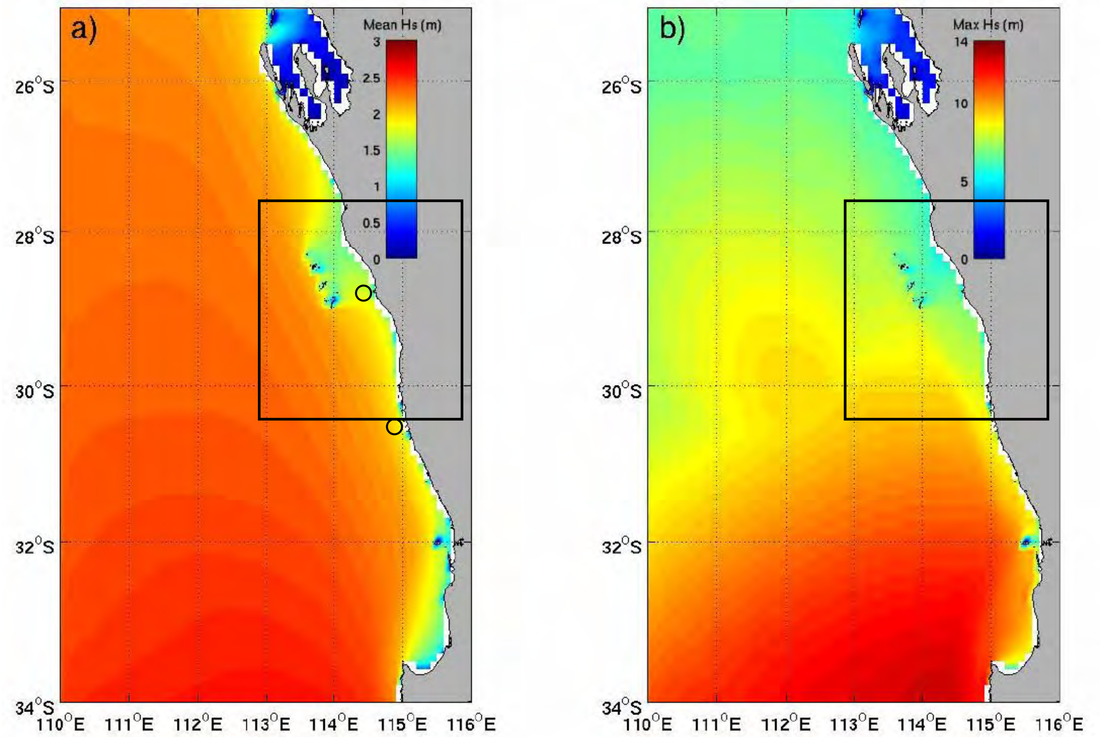


Figure 4-15: Indicative Variation of Significant Wave Heights for Geographe Bay to Cape Inscription (February 1997 – February 2004)
(a) Mean and (b) Maximum
(After: Richardson et al. 2005)
Note: Study Area Shown in Black Box and Wave Buoys as Black Circles

Considerations of directional range and seasonal shifts in swell direction have previously been investigated for Rottnest Island, south of the Study Area. A broad directional range of high swell energy from 240 to 280° is recorded and reported for Rottnest, with prevailing swell from the south to southwest, with enhanced west to northwest activity during winter months (Roncevich *et al.* 2009; Eliot *et al.* 2012a). Approximately 6% of the swell wave energy during 2006 arrived from north of west, but this only arrives during winter months, or extremely rarely in summer during southwards tracking tropical cyclones such as occurred in 2011. This confirms a nett seasonal shift in swell direction described for the Perth coastline qualitatively (Masselink & Pattiaratchi 1998) and quantitatively for 2004 to 2009 (Roncevich *et al.* 2009). However, analysis of synoptic system variability suggests that the quantity of change may vary significantly between years (Steedman & Associates 1982; Panizza 1983). This synoptic variability has been translated to wave variability by Bosserelle *et al.* (In Press) through a 40 year modelling investigation of track and intensity of large wave events in the Southern Indian Ocean that affect the south-west WA Coast.

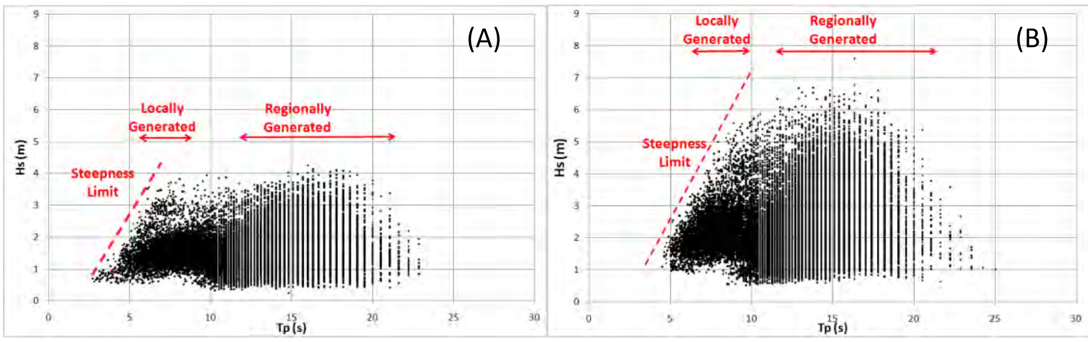


Figure 4-16: Wave Height and Period Crossplots (1999-2006)
(A) Geraldton and (B) Jurien

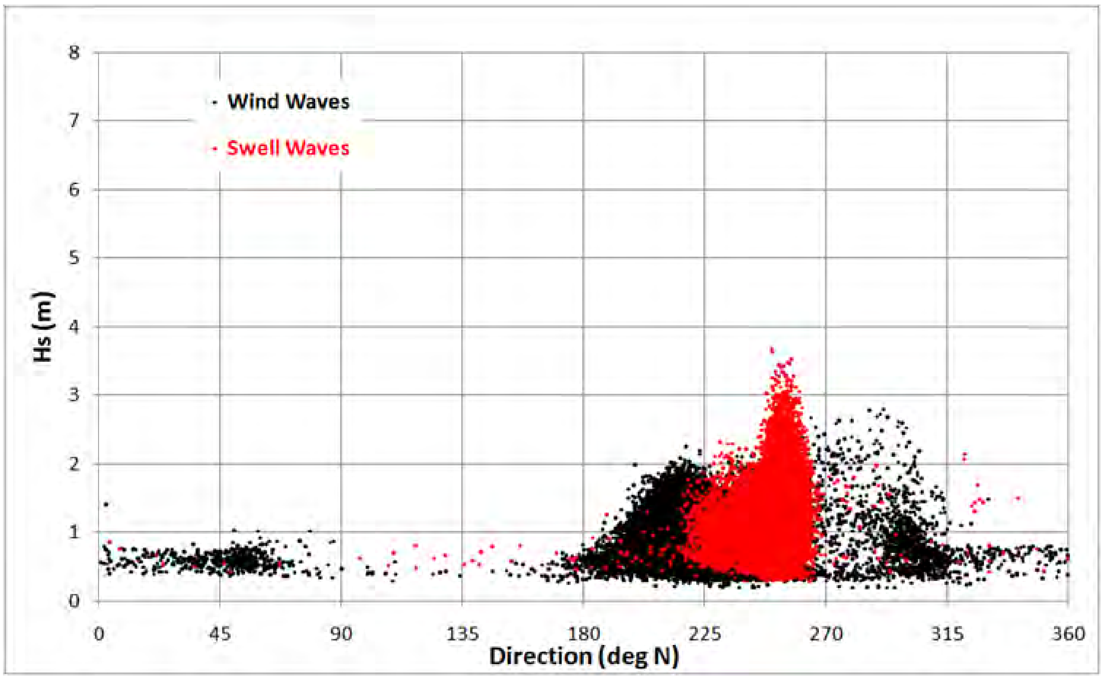


Figure 4-17: Wave Height and Direction for 2006 for Geraldton

The seasonal distribution of wave heights shows a peak from May to September across the region (Figure 4-18). Variability between sites may be attributed to a combination of factors including weather system type and track, along with local intensification of winds.

Extreme events are shown by the peak in the 99th percentile (Figure 4-18). Extreme wave heights, particularly associated with high water level events, can result in acute storm erosion. It is appropriate to note that the preparation of any extreme distribution curves strongly reflects stormy periods and therefore is highly affected by inter-annual variability of the wave conditions. Any extreme distribution curves should be interpreted with caution due to the short length of the datasets.

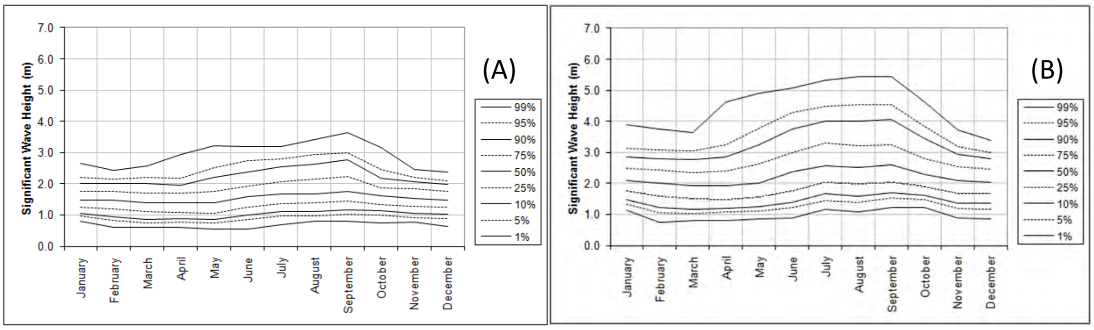


Figure 4-18: Seasonal Distribution of Wave Heights
(A) Geraldton (1999-2006) and (B) Jurien (1999-2009)

The perception of trends and variability in the Western Australian extreme wave climate is limited by the relative availability of environmental data sets. Observational data from permanent monitoring stations are available from 1994, with inferred wave conditions via altimetry from 1985 or by modelled wave hindcast from 1970. Early data are recognised as having lower quality, and cannot be independently validated. The measured wave record at Rottnest (1994 to present) shows a natural inter-annual variability in larger waves of approximately 22% (Eliot *et al.* 2012a).

The investigation of variability has been extended through the use of satellite altimetry, with accuracy and sampling frequency limitations. Young *et al.* (2011) used 23 years (1985-2003) of satellite altimetry inferred wave heights to determine a trend of approximately +0.5% per annum in 90% occurrence significant wave heights offshore of SW WA over the period. This corresponds to an approximate increase from 5 m wave height to 5.6 m over the 23 years.

A wave modelling investigation of the Southern Indian Ocean over the last 40 years (1970 to 2009) extends the wave record to consider the natural variability, with a 30-50% annual variability of significant wave height (Bosserelle *et al.* In Press), which is greater than the 22% determined from the measured buoy record at Fremantle. Bosserelle *et al.* (In Press) have attempted to account for this variability over the 40 year record, determining there is no statistically significant trend in extremes (90% occurrence significant wave height), with a +0.006m/yr change in mean wave height over the 40 year modelled record. There is no discernable trend in extreme wave heights, including large swell events, when considering the longer record. An increased number of large wave events in the southern Indian Ocean have been observed, offset by tendency for storm systems to track further southwards relative to WA (Bosserelle *et al.* In Press).

Further 20 year wave hindcasts have been prepared north of Geraldton for the planned Oakajee Port development (RPS Metocean; Table 4-18; Section 4.3.3.4)

The local effects of the reef, island and bank structure on the inshore wave climate is discussed in Section 4.3.3.

4.2.4. Currents

Limited information has been collected regarding nearshore currents in the Mid-West area, with the majority of available information relevant to describing regional offshore currents or generated using numerical models.

In theory, four principal current drivers are oceanographic (steric gradients and weather systems), tidal, wind-driven (local winds) and wave driven processes, each of which is likely to be dominant in a different zone relative to the coast and lagoons. Consequently, there is a theoretical sequence of currents moving seawards that relates to the relative strength of the forcing mechanisms (Figure 4-19; Damara WA 2010).

Regional currents have been examined using satellite imagery, drifters, gliders, boat based measurements and long-term current metering deployment at the Houtman Abrolhos (Cresswell *et al.* 1989; Pearce & Pattiaratchi 1997). These investigations provide a general focus on surface currents, the Leeuwin Current and weather system forcing, including eddy formation and influences of islands (Zaker *et al*. 2007).

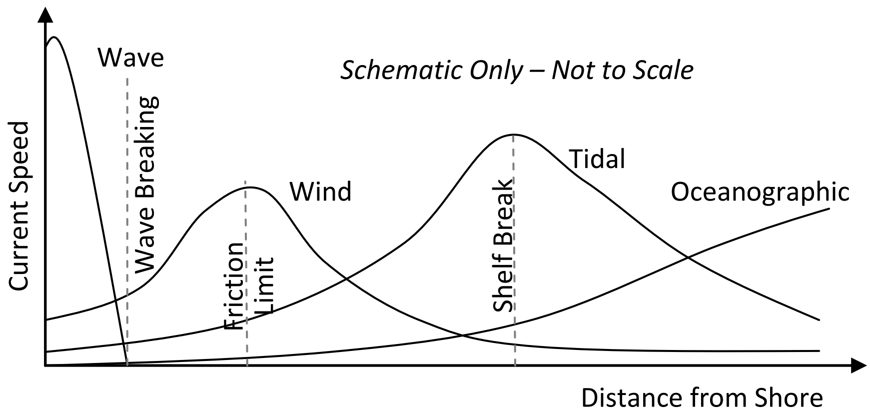


Figure 4-19: Schematic Spatial Distribution of Currents (Source: Damara WA 2010)

In general, the boundary effect of the coast causes most surface currents in the nearshore to run nearly shore parallel. This pattern can be modified by the influence of reef and islands, discussed in Section 4.3.3. Further offshore the surface current direction becomes more responsive to the direction of forcing. Tidal currents become more shore-normal near the shelf break (Damara WA 2010).

Investigation of the dispersion of dredge disposal for the proposed port developments at Oakajee (APASA 2009) and Geraldton (GEMS 2001) has provided the main motivation for nearshore current measurements and modelling within the Study Area. Additionally, drifter measurements were conducted to consider sediment movement at the site of the Port Denison Harbour (PWD 1976) and at the Murchison River mouth, Kalbarri (Bailey 2005). The model domain for the Oakajee study extended from Cape Burney to Port Gregory and was verified against measured currents at Oakajee (6.5m and 20m depths) and Geraldton port (12.5m depth) (APASA 2009). The model domain for the Geraldton study extended from south of Point Moore to Champion Bay, with no model verification (GEMS 2001).

4.2.5. Hydrology

Rivers have the potential to affect the supply of sediment to the coast, and may either act as a sediment sink or source (Section 3.3.3). The behaviour is highly dependent upon the catchment structure and hydrology, but also varies in time responding to episodic flooding and a general pattern of sediment release during episodic floods and sediment capture during lower flows. The Mid-West rivers are generally blocked by ocean entrance bars, limiting their capacity for sediment exchange. The Murchison River provides a major exception, trapping approximately 60,000 m^3p.a. of marine sediments, but with the capacity to release more than 100,000 m^3 in a single flood event, such as TC Emma in 2006.

There are nine main rivers and creeks that discharge into the Mid-West coast, contained within the Greenough and Murchison Drainage Basins as part of the larger Indian Ocean Division (Figure 4-20; Landvision & UWA 2001; WRC 1997). The three main rivers of the Greenough Drainage Basin are the Irwin, Greenough and Chapman rivers, with further influence of five rivers including Buller, Oakajee, Oakabella, Bowes and Hutt (Figure 1-1; Figure 4-20B). The major river for the northern drainage basin is the Murchison River (Figure 4-20A). Other river systems (such as the Arrowsmith) discharge into coastal lakes or inland salt lakes such as Lake Austin, or submerge into the groundwater system, some outcropping on the inner shelf (Johnson & Commander 2006).

The hydrologic network is gauged and monitored by the Department of Water, with rainfall monitored by the Bureau of Meteorology. The gauging stations used herein are listed in Table 4-10 and labelled in Figure 4-1.

The influence of rivers varies along the Mid-West coast in terms of flooding potential and influence on the sediment budget, and is considered a locally significant factor for some of the Areas of Planning Interest (Section **6**). The four major rivers of the Mid-West (Irwin, Greenough, Chapman and Murchison) are estimated to provide a similar order of magnitude of terrestrial sediments to the coast (Table 4-11). This is a significantly smaller contribution than the Fitzroy and Ord Rivers in northern Australia (Table 4-11). The values presented in Table 4-11 are mean annual estimates with significant inter-annual fluctuations (BoM 1998; NLWRA 2001; Li *et al.* 2008).

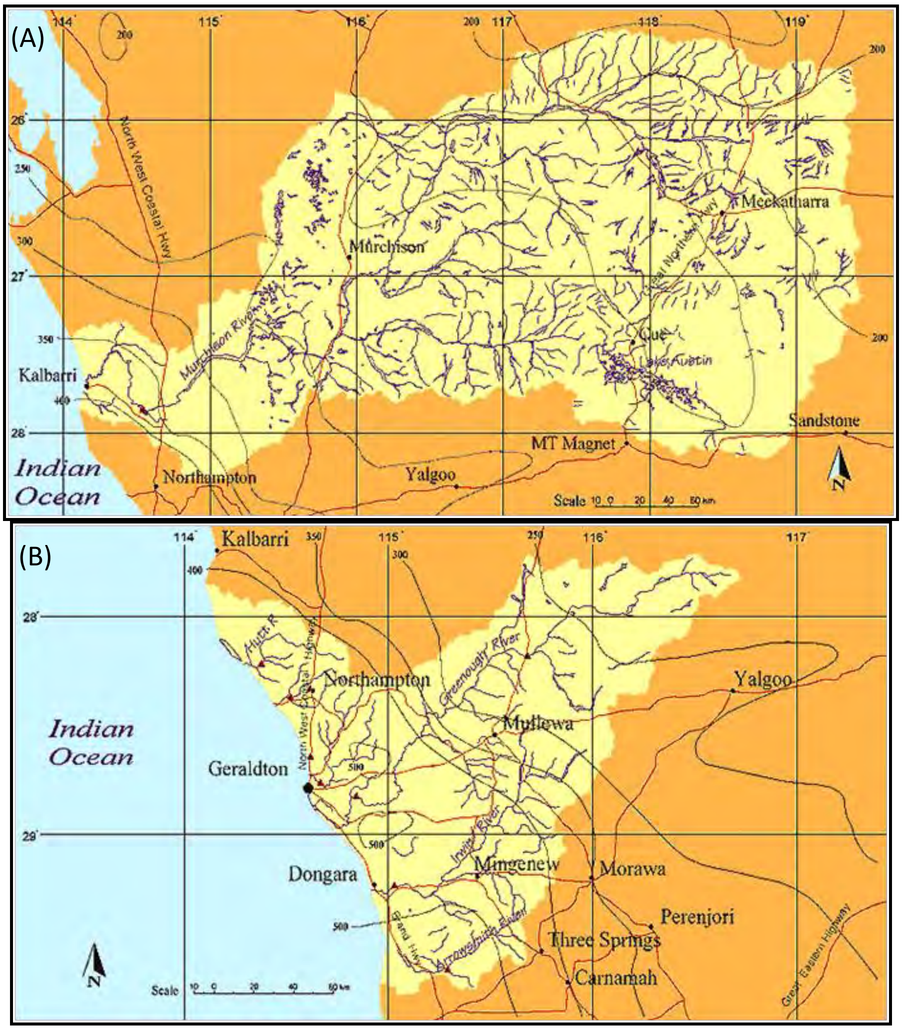


Figure 4-20: River Catchments
(A) Murchison, (B) Greenough
(Source: Department of Water)

The river influence on the coast is dependent on the following factors (following from Section 3.3.3):

- Catchment and river channel characteristics, including natural vegetation coverage (Figure 4-21) and the level of saturation of the catchment;
- River flow. A higher river flow at the mouth will have greater potential for contribution of sediment to the coastal system due to an increased carrying capacity and potential erosive force (Table 4-11);
- Structure of the river mouth, delta and/or estuary – The geological structure, adjacent landforms and form of the river bar, delta and/or estuary may also provide direct control on erosion during flood events. Hence they also affect the mobility of the sediments at the river mouth and the likelihood of the river acting as a sediment sink (Section 3.3.3; Figure 4-23).
- Significance of previous flood (s) – The behaviour of the river system and delta as a source or sink of sediment will be dependent on the amount of sediment scoured during the previous flood and the time since the prior flood. Flood sequencing can significantly deplete a delta, river mouth and the lower reaches of sediment.

Table 4-10: Rainfall and River Discharge Observations Incorporated for the Mid-West Coast (Source: Bureau of Meteorology and Department of Water)

Location	Station	Lat. (S)	Long. (E)	Data	Installed	Distance Upstream from mouth
Murchison River						
Kalbarri	8251	30.308°	114.165°	Rainfall	1970	N/A
Sherwood	7078	26.560°	118.540°	Rainfall	1926	N/A
Emu Springs	702001	27.855°	114.546°	Streamflow	1967	95km
Hutt River						
Yerina	701010	28.218°	114.380°	Streamflow	1992	11km
Chapman River						
Utakarra	701007	28.763°	114.669°	Streamflow	1976	10km
Greenough River						
Geraldton Airport	8051	28.795°	114.698°	Rainfall	1941	N/A
Mullewa	8095	28.537°	115.514°	Rainfall	1908	N/A
Karlenew Peak	701002	28.824°	114.846°	Streamflow	1971	50km
Irwin River						
Mountain Bridge	701009	29.238°	115.035°	Streamflow	1982	18km

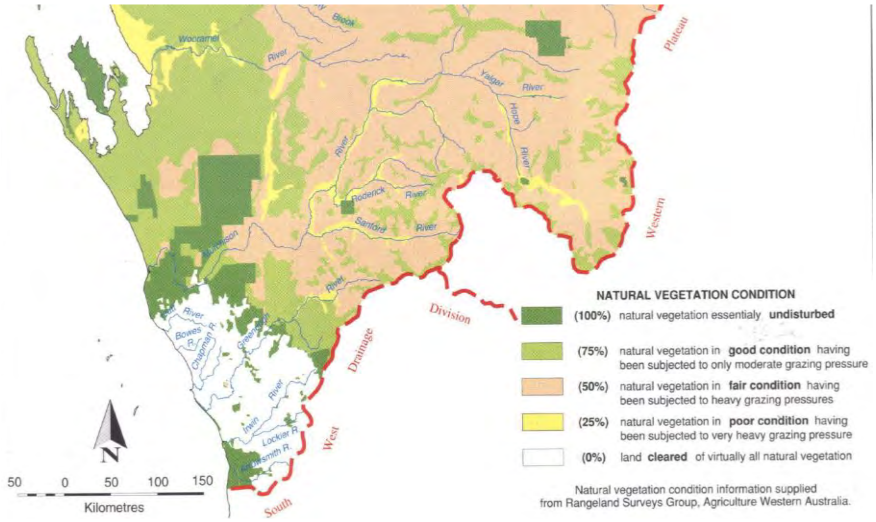


Figure 4-21: Natural Vegetation Condition of the Rivers (Source: WRC 1997)

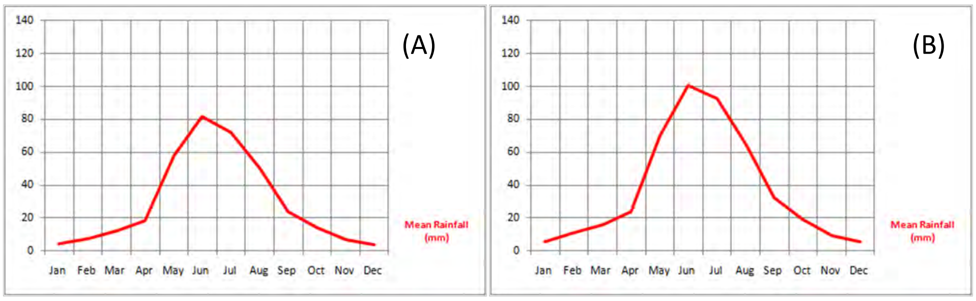


Figure 4-22: Mean Monthly Rainfall at (A) Kalbarri and (B) Geraldton (Source: Bureau of Meteorology)

Table 4-11: Major Rivers and Potential Sediment Supply
Rivers within the Study Area are Shaded
(Source: Li *et al.* 2008)

Sediment Source	Catchment Area (km^2)	River Flow (GL/y)	Suspended Sediment Export to the Coast (kT/y)	Mean Annual River Outflow at the Mouth Q (m^3/s)	Mean River Sediment Concentration C (kg/m^3)
Ord	85,213	9,448	600	300	0.063
Fitzroy	103,900	4,800	2,635	152	0.549
Gascoyne	78,548	1,117	Not Reported	35.4	0.023
Murchison	89,184	410	21	13	0.049
Hutt	1,254	50	11	1.6	0.219
Chapman	1,644	93	19	2.9	0.202
Greenough	12,568	44	28	1.4	0.63
Irwin	3,721	186	32	5.9	0.17
Moore	13,540	396	21	12.7	0.05

Murchison (Kalbarri)	Irwin (Dongara/Port Denison)	Oakabella
Geological control across open mouth	Intermittently open mouth controlled by rock outcrops	Streams with lower flow and constrained between cliffs
Bar mainly open	Bar intermittently open	Bar mainly closed
Most potential sediment supply	Moderate potential sediment supply	Least potential sediment supply
	Also: Greenough, Chapman, Hutt	Also: Buller, Oakajee, Woolawar Gully, Bowes

Figure 4-23: River Mouth Structure and Sediment Supply

4.2.5.1. Irwin River

The Irwin River catchment is 5,264 km^2 above the Mountain Bridge gauging station, located approximately 18 km upstream of the Irwin River mouth (Figure 1-1; Figure 4-20B). The Irwin River is 135 km long passing largely through cleared sandy and erosional plains (State Planning Commission 1998; ATA 2005a), flowing through parabolic dunes for the final 1km prior to the mouth at Dongara/Port Denison (**Figure C - 37** Appendix C). Alluvial flats are present from 1 to 3km upstream of the mouth, mainly on the northern side of the present river channel. The mouth is topographically controlled by the dunes and underlying coastal limestone (State Planning Commission 1998). The river has a barred mouth that is intermittently open, and is susceptible to flash flooding (Department of Agriculture 2005). The Irwin River middle and lower reaches are sustained by perennial flow due to discharge from the groundwater systems (Department of Agriculture 2005).

A hydrologic study to estimate the 100 year Average Recurrence Interval (ARI) flood levels for the Irwin River at Dongara was prepared by the Water Authority of Western Australia (WAWA 1986a). However this study did include the May 1999 flood event. This level is at less than 1.8mAHD towards the southern extent of the estuary (ATA 2005a).

The peak monthly discharge for the Mountain Bridge station is presented in Figure 4-24, with station location listed in Table 4-10 and labelled in Figure 4-1. The ten maximum recorded flows at the Mountain Bridge gauging station are presented in Table 4-12, with the maximum recorded event of 1707 m^3s^{-1} in May 1999 associated with a mid-latitude depression raining on a saturated catchment following TC Vance in March 1999. This event also recorded the second highest peak discharge for the Irwin River and highest for the Chapman River. Major floods are reported in 1971, 1988, 1989, 1996 and 1999 (Department of Agriculture 2005), along with the recent 2011 flooding associated with TC Dianne.

River flows are typically low, with episodic flows in flood events, with the ten maximum discharge events occurring during the higher rainfall period May to August or during infrequent summer tropical cyclones (Shire of Irwin 2007; Figure 4-22B; Figure 4-24; Table 4-12).

The sediment supplied by the Irwin River (and its bar) contributes to the littoral drift system immediately to the north (PWD 1976) and may be a contemporary source of sediment to the blowouts at Nine Mile Beach to the north. The Irwin River carries estimated mean suspended sediment loads of 32.10 kT/year (Table 4-11; Li *et al.* 2008).

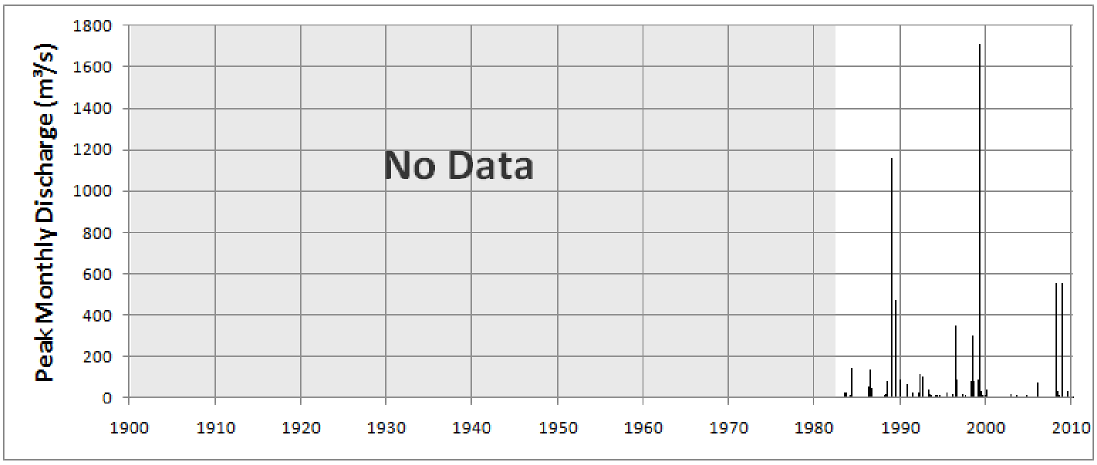


Figure 4-24: Peak Monthly Discharge at Mountain Bridge approximately 18 km upstream of the Irwin River mouth (Source: Department of Water)

Table 4-12: Ten Largest Peak Discharge Events for the Irwin River (1982-2010)
Note: May 1999 event was due to a mid-latitude depression and a saturated catchment

Year	Month	Peak Discharge (m^3/s)
1999	May	1,707
1988	December	1160
2008	March	552
2008	December	552
1989	June	472.3
1996	July	349.6
1998	July	298.1
1984	May	144.8
1986	June	133.1
1986	July	131.3

4.2.5.2. Greenough River

The Greenough River catchment is 11,737 km^2 above the Karlenew Peak gauging station, located approximately 50 km upstream of the Greenough River mouth at Cape Burney (Figure 1-1; Figure 4-20B). The total catchment area of 19,500 km^2 extends 250 km northeast of the mouth (JDA 2006). The river travels southwest from the Yilgarn Block through coastal sandplains until it is diverted north by a parabolic dune barrier (WRC 2001a; JDA 2006; **Figure C - 31** Appendix C). The Greenough River Flats, alluvial flats of approximately 1 to 2km width are located between 3 and 10 km upstream of the mouth, provide attenuation of flood flows. The present river mouth location is controlled by the limestone rock outcrops to the north and south and by the dunes. The river has a barred mouth that is blocked by foredunes in summer and is breached during winter flows (WRC 2001a; Figure 4-26). When the bar is open the tidal influence extends 7km upstream of the mouth (WRC 2001a).

The coastal (Geraldton) and inland (Mullewa) monthly rainfall is presented in Figure 4-25, along with the peak monthly discharge for Karlenew Peak. Station locations are listed in Table 4-10 and labelled in Figure 4-1. The ten maximum recorded flows at the Karlenew Peak gauging station are presented in Table 4-13, with the maximum recorded event of 732.2 m^3s^{-1} in January 2006 associated with ex-TC Clare. The rainfall record at Mullewa extends 64 years longer than the streamflow gauge at Karlenew Peak. This suggests the potential for greater floods to occur than have been recorded since 1971, with at least two individual months between 1908 and 1971 receiving monthly rainfalls in excess of the maximum monthly rainfall for the period of streamflow record (1971-2010). Major floods were reported in 1888, 1927, 1953, 1963, 1970, 1971, 1988, 1994 and 1999 (Department of Agriculture 2005; JDA 2006), with additional floods in 2006 (TC Clare) and 2011 (TC Dianne).

The original hydrologic study to estimate 25, 50 and 100 year Average Recurrence Interval (ARI) flood levels for the Greenough River (WAWA 1986b) was updated in 2006 for the Department of Water, including provision of 100 year peak flow estimates (JDA 2006). The 100 year flow estimate increased from 1,100 m^3s^{-1} to 1,620 m^3s^{-1} at Karlenew Peak, which was a similar order of magnitude to the 1888 flood (JDA 2006). The flood levels at the river mouth are significantly less than at Karlenew Peak due to the attenuation by the Greenough River Flats (JDA 2006).

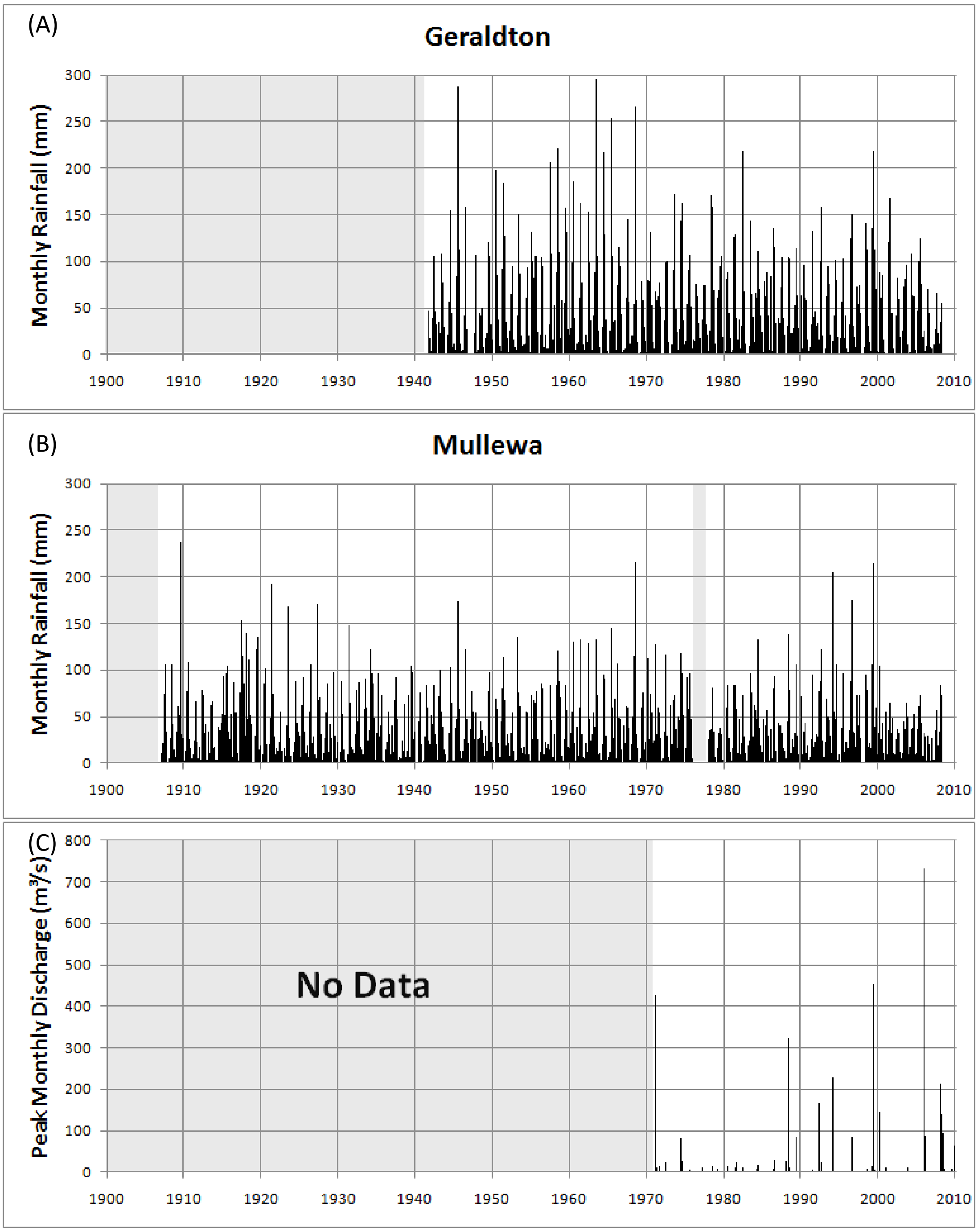


Figure 4-25: Rainfall at Selected Locations and Discharge for the Greenough River (A) Coastal Station at Geraldton, (B) Inland Station at Mullewa and (C) Peak Monthly Discharge at Karlenew Peak approximately 50 km upstream of the Greenough River mouth (Source: Bureau of Meteorology and Department of Water)

River flows are typically low, with episodic flows in flood events, with the ten maximum discharge events occurring during infrequent summer tropical cyclones or during the higher rainfall period May to August (JDA 2006; Figure 4-22B; Figure 4-25C; Table 4-13). The 2006 flood event associated with TC Clare opened the bar, forming a channel 50 to 90m wide (Figure 4-26; Pearson 2006; Tecchiato & Collins 2011).

Table 4-13: Ten Largest Peak Discharge Events for the Greenough River (1971-2010)

Year	Month	Peak Discharge (m^3/s)
2006	January	732.2 (TC Clare)
1999	May	453.3 (mid-latitude depression on saturated catchment)
1971	March	425.4 (TC Mavis)
1988	May	322.1
1994	March	229
2008	February	212.5
1992	April	167.7
2000	March	146.6
2008	April	141.2
2008	May	93.76

Figure 4-26: Greenough River Mouth in Flood January 2006 (ex-TC Clare) (After: Pearson 2006)

The Greenough River carries estimated mean suspended sediment loads of 28kT/year, which represents a low yield relative to its catchment area (Table 4-11; Li *et al.* 2008). The sediment supplied by the Greenough River, other than the mobilisation of bar sediments, is not anticipated to regularly contribute directly to the littoral drift system to the north. Sediment investigations by MP. Rogers & Associates (1996) and Tecchiato & Collins (2011) found that beaches adjacent to the river are largely composed of fine carbonate sands (85-98% carbonate), which is of marine origin. The riverbed sediments are largely red sands and loams (WRC 2001a) with the February 2011 flooding mainly transporting suspended mud and bedload cobbles (Tecchiato & Collins 2011).

4.2.5.3. *Chapman River*

The Chapman River catchment is 1,579 km^2 above the Utakarra gauging station, located approximately 10 km upstream of the mouth (Figure 1-1; Figure 4-20B). The Chapman River is 104 km long travelling southwest through the cleared sandplains of the northern Perth Basin and the granites and alluviums of the Northampton Block through parabolic dunes to the mouth at Sunset Beach in Geraldton (WRC 2001b; Department of Agriculture 2005). An area of alluvial flats is located between parabolic dunes from 0.5 to 1.5km landward of the present beach (**Figure C - 27** Appendix C). The mouth is geomorphologically controlled by the dunes. The river has a barred mouth that is open to the ocean during peak winter flows, particularly coincident with high tide (WRC 2001b). The Chapman River middle and upper reaches receive discharge from the groundwater systems (WRC 2001b).

The Department of Water has determined 10, 25 and 100 year Average Recurrence Interval (ARI) flood levels for the Chapman River, with 100 year ARI floodplain mapping (Simon Rodgers, Department of Water, *pers. comm*.).

The peak monthly discharge for the Utakarra station is presented in Figure 4-27, with station location listed in Table 4-10 and labelled in Figure 4-1. The ten maximum recorded flows at the Utakarra gauging station are presented in Table 4-14, with the maximum recorded event of 1707 m^3s^{-1} in May 1999 associated with a mid-latitude depression raining on a saturated catchment following TC Vance in March 1999. Major floods were reported in 1888, 1934, 1939, 1960, 1971, 1986, 1996, 1999 (Department of Agriculture 2005; Shire of Chapman Valley 2008), with the 1971 flood levels exceeding the 1999 levels.

River flows are typically low, with episodic flows in flood events, with the ten maximum discharge events occurring during infrequent summer tropical cyclones or during the higher rainfall period of May to August (Figure 4-22B; Figure 4-27; Table 4-12; Department of Agriculture 2005; Shire of Chapman Valley 2008). Rain falling on the hard setting soils in the catchment can lead to rapid flooding of the Chapman River, including the potential for flash flooding (Shire of Chapman Valley 2008).

The Chapman River carries estimated mean suspended sediment loads of 19kT/year, a relatively high sediment yield for the small catchment area (Table 4-11; Li *et al.* 2008). The sediment supplied by the Chapman River is a combination of sediments from the catchment and contained within the bar. The bar is approximately 100m wide (Short 2005) with channels occurring through the bar during flood events observed in 1999, 2004 and 2007 (Tecchiato & Collins 2011). The river is supplying quartz-dominated sand and garnet, with some carbonate (Tecchiato & Collins 2011). A significant proportion of the sediment supplied by the river system may deposited in the centre of Champion Bay, with present investigations being conducted into the potential contribution to the beaches north and south of the Chapman River (Tecchiato & Collins 2011).

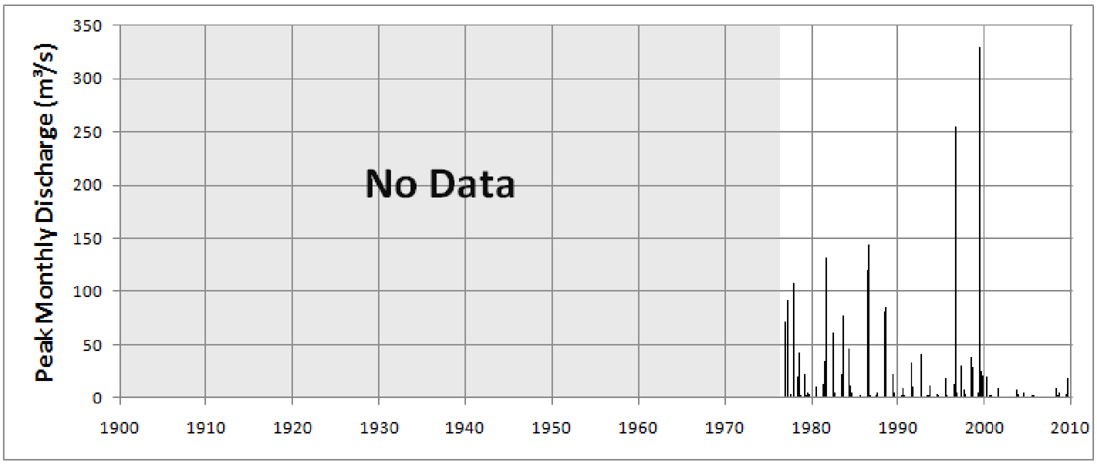


Figure 4-27: Peak Monthly Discharge at Utakarra approximately 10 km upstream of the Chapman River mouth
(Source: Department of Water)

Table 4-14: Ten Largest Peak Discharge Events for the Chapman River (1976-2010)
Note: May 1999 event was due to a mid-latitude depression and a saturated catchment

Year	Month	Peak Discharge (m^3/s)
1999	May	329.5
1996	July	254.9
1986	July	144.4
1981	August	132.4
1986	June	119.7
1977	December	108
1977	April	91.54
1977	November	91.54
1988	July	85.67
1996	August	83.11

4.2.5.4. Buller, Oakajee, Oakabella, Bowes and Hutt Rivers

Five additional rivers draining to the ocean in the Study Area are the Buller, Oakajee, Oakabella, Bowes and Hutt Rivers (Figure 1-1; Figure 4-20B). Some of the soils are hard setting, leading to rapid and high levels of runoff in significant rainfall events, such as those associated with dissipating tropical cyclones (Shire of Northampton 2008). In times of flood, many of the rivers have the capacity to flood areas adjacent to their channels, entraining sediment that could be discharged to the coast. These five rivers drain through the Northampton complex producing quartz and garnet grains.

The majority of data on flood levels are anecdotal or rely on local knowledge (Shire of Northampton 2008). The Yerina station on the Hutt River has operated since 1992 (Figure 4-1), with the Buller station on the Buller River operating from 1974 to 2001. Further gauging stations are presently proposed in the area (Aquaterra 2007), but may not adequately capture the patchiness of the rainfall and resultant flash flooding.

The Buller and Oakajee Rivers discharge between Buller and Coronation Beaches (Cell 48). The proposed Oakajee Port is intended to be located between the Buller and Oakajee river mouths (Aquaterra 2009). The Buller River rises in the Moresby Range, is approximately 10km long with a catchment area of 33 km^2 (Short 2005; Aquaterra 2009). The river drains through colluvial footslopes largely cleared of vegetation, with the mouth constrained by dunes and a limestone headland to the south, and a dune blowout to the north (**Figure C - 25**; **Figure C - 27** Appendix C). It is usually a dry stream, with the river mouth frequently closed, with flows occurring after heavy rain (Aquaterra 2009; Tecchiato & Collins 2011).

The Oakajee River also rises in the Moresby Range, is approximately 12km long with a catchment area of 35 km^2 (Aquaterra 2009). The proposed Oakajee Port is located opposite the river mouth. The river drains through colluvial footslopes, cliff footslopes and alluvial terraces largely cleared of vegetation, with the mouth constrained by dunes and a foredune plain (**Figure C - 25**; Appendix C). The river can break part of the bar during flows following heavy rain.

The Oakabella Creek and Woolawar Gully (immediately to the north) discharge to the largely cliffed coast between Coronation Beach and Bowes River (Cell 49). The creeks flow through largely cleared colluvial footslopes, cliff footslopes, alluvial terraces and the Northampton Complex, with the mouths constrained by dunes and cliffs (**Figure C - 23**; Appendix C).

The Bowes River drains farming areas around the Waterloo Range, providing sediments to the Bowes River to Whale Boat Cove sediment cell (Cell 50), which includes the townsite of Horrocks. The lower reaches of the river flow through largely cleared alluvial terraces, which have the potential for flooding, through parabolic dunes and blowouts (Shire of Northampton 2008; **Figure C - 21** Appendix C). The river periodically breaks the bar during significant flow events, mainly during the months of June to August (Department of Agriculture 2005).

The Hutt River also drains largely cleared farming areas around the Waterloo Range, possibly providing sediments to the beaches between Broken Anchor Bay to Eagles Nest (Cell 54) and to the Broken Anchor Bay to Shoal Point Tertiary Compartment (Landvision & UWA 2001). This area includes the townsite of Port Gregory, approximately 5km northwest of the river mouth. The Hutt catchment is 1,078 km^2 above the Yerina gauging station, which is 10 km upstream of the mouth (Figure 4-1). The lower reaches of the river flow through largely cleared alluvial terraces and alluvial flats, which have the potential for flooding (Shire of Northampton 2008; **Figure C - 15**; **Figure C - 17** Appendix C). The river is associated with a coastal lagoon, the Hutt Lagoon, with the mouth geomorphologically controlled by the dunes and blowouts to the southeast. The Hutt River carries estimated mean suspended sediment loads of 11kT/year, which represents a relatively low yield for the catchment size (Table 4-11; Li *et al.* 2008).

4.2.5.5. Murchison River

The Murchison River catchment is 86,777 km^2 above the Emu Springs gauging station, located approximately 95 km upstream of the Murchison River mouth at Kalbarri (Figure 1-1;

Figure 4-20A). The total catchment area of 91,254 km^2 extends 550 km inland of the mouth (WRC 1997; Magee 2009). The river flows largely through sandstones, greenstone and granitoids (Hocking *et al.* 1982; Hocking 1991; Johnson & Commander 2006; **Figure C - 3**; **Figure C - 5** Appendix C). Upstream of the mouth and initial dune field to the north, alluvial flats of approximately 1km width are adjacent to Sandstone deposits. The river mouth location is controlled by Oyster Reef, and further limestone outcropping to the south (Bailey 2005; **Figure C - 4** Appendix C), with the dunes to the north of the mouth and the spit at Chinaman's Beach susceptible to removal during large flood events (Bailey 2005). The river discharges to a naturally wave-dominated delta, with the bar at the mouth permanently kept open by maintenance dredging (Landvision & UWA 2001). The tidal influence extends 12-20 km upstream of the mouth (Bailey 2005 after Hesp 1984).

The coastal (Kalbarri) and inland (Sherwood) monthly rainfall is presented in Figure 4-28, along with the peak monthly discharge for Emu Springs. Station locations are listed in Table 4-10 and labelled in Figure 4-1. The ten maximum recorded flows at the Emu Springs gauging station are presented in Table 4-15, with the maximum recorded event of 1,789 m^3s^{-1} in March 2006 associated with rainfall from ex-TC Emma falling on a saturated catchment. Major floods were reported in 1926, 1960, 1974, 1975, 1980, 1989, 1992, 1995 and 2000 (Department of Agriculture 2005; Bailey 2005; Bureau of Meteorology 1998, 2006), with additional floods in 2006 (TC Emma) and 2011 (TC Dianne).

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

River flows are typically intermittent, with episodic flows in flood events sustained for long periods following heavy rainfall (Laws 1992). The ten maximum discharge events occurred during January to March, associated with tropical lows or tropical cyclones, with further flooding during a succession of northwest cloud band events during the cooler months of May to July or flash flooding associated with thunderstorms (Bureau of Meteorology 1998; Figure 4-28C; Table 4-15).

The Murchison River carries estimated mean suspended sediment loads of 21kT/year to the coast (Table 4-11; Li *et al.* 2008), which is significantly lower proportionally to the flow and catchment area of the other Mid-West catchments. However, the landforms at the river mouth contain a larger volume of sediment than other Mid-West rivers that behave as temporary sediment sinks, occasionally mobilising during significant flood events (eg. **Figure 6-11**). These landforms in the estuary, sand spit, bar and dune blowouts contain a mixture of sediments of marine and terrestrial origin (Bailey 2005). The behaviour of the river mouth in relation to the river and coastal littoral drift has been investigated by Bailey (2005; following DMH 1989 and CIES 1996) in relation to the annual dredge volumes required to maintain a navigable entrance. These studies suggest that the river mouth landforms are mobilised during large river flows, nett littoral drift estimates are approximately 27,000-33,000 m^3/yr and approximately 20,000-35,000 m^3/yr of sediment is dredged from the channel (DMH 1989; Bailey 2005). An estimated 200,000-400,000 m^3 of material was deposited seaward of the mouth following TC Emma in 2006. Following a significant flood event, it is likely that a large proportion of the nett littoral drift will be entrained into the flood scoured areas.

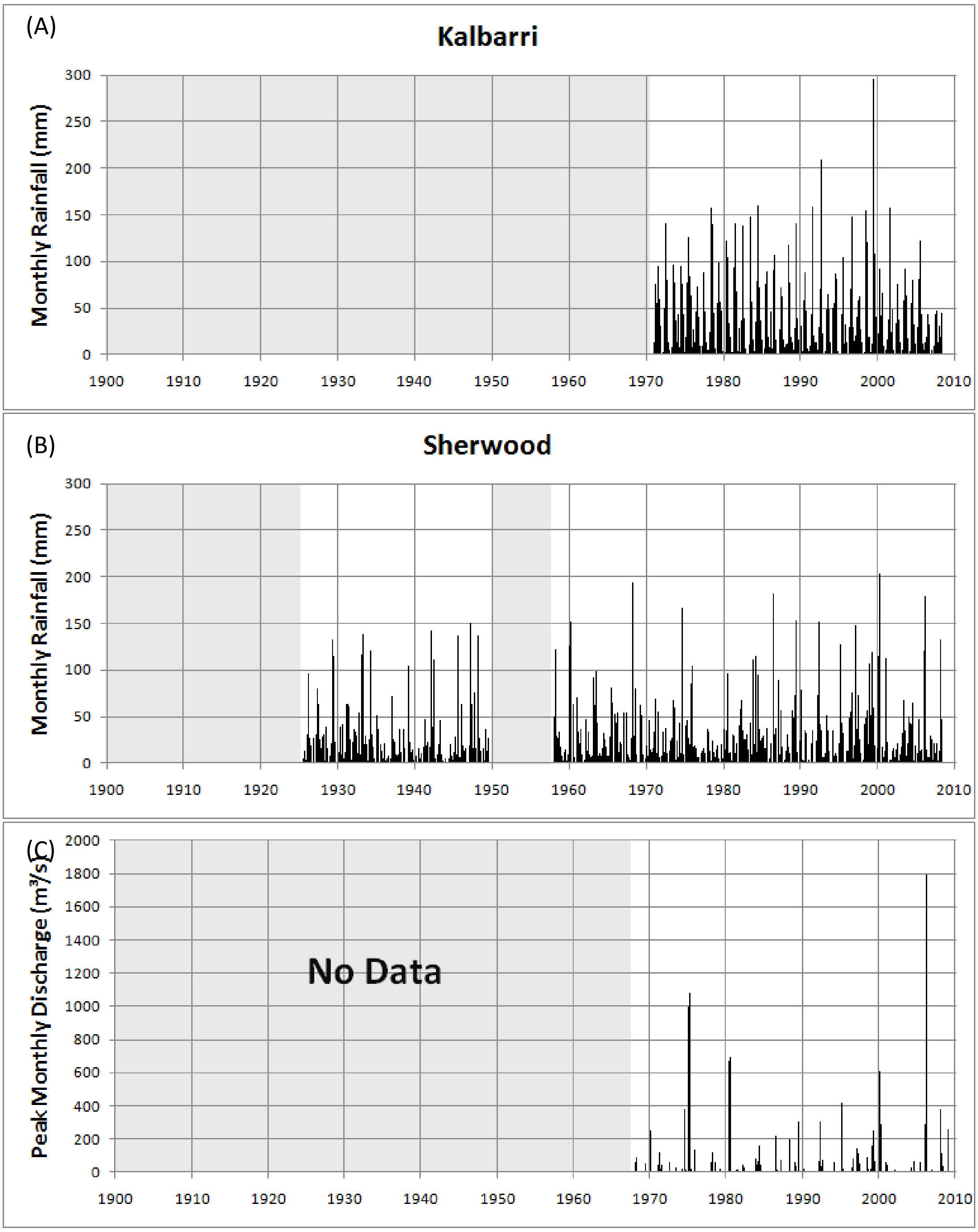


Figure 4-28: Rainfall at Selected Locations and Discharge for the Murchison River (A) Coastal Station at Kalbarri, (B) Inland Station at Sherwood and (C) Peak Monthly Discharge at Emu Springs approximately 95 km upstream of the Murchison River mouth (Source: Bureau of Meteorology and Department of Water)

Table 4-15: Ten Largest Peak Discharge Events for the Murchison River (1967-2010)

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

4.2.6. Groundwater

Beaches with elevated groundwater generally have greater instability as saturated sediments are more prone to entrainment by waves. Lower groundwater levels enhance deposition and the unsaturated sediments are increasingly available for aeolian transport along the beach and into the dunes. Low frequency shoreline fluctuations with recurrence intervals of 0.5-10 years can occur due to varying groundwater conditions (Clarke & Eliot 1987).

Regional groundwater behaviour is summarised in Johnson & Commander (2006) from Green Head to Nunginjay Springs Coast North, with the Arrowsmith area south of Geraldton described in WAWA (1995). Many of the groundwater investigations in the area relate to groundwater management for use in town and resource water supplies, regional park management and for management and environmental water requirements of wetlands and rivers. Groundwater studies are generally associated with river catchments. Further studies describe the groundwater behaviour for:

- Coastal wetlands area from North Head to north of Coolimba: Kern (1997), Rutherford *et al.* (2005), Department of Agriculture & Food (2007);
- Irwin river: Shire of Irwin (2007);
- Greenough river: JDA (2006); and
- Murchison catchment: Laws (1992), Magee (2009).

There are both deep and shallow aquifers in the region. Groundwater flow sustains wetlands from North Head to Coolimba, with a general decrease in the average groundwater levels with distance north of Geraldton. Flow is generally west off the scarp onto the coastal plain, with flow from the scarp also draining inland to saline lakes (Johnson & Commander 2006). The surficial aquifer discharges groundwater at the shoreline over a saltwater interface. Flow locally occurs towards rivers.

Groundwater levels vary spatially and temporally. From North Head to Coolimba, the creeks and groundwater flow from the scarp to accumulate in a series of coastal wetlands (Kern 1997). The groundwater levels adjacent to the coast decrease north of Coolimba (Rutherford *et al.* 2005). North of Geraldton, the groundwater of the coastal plain (to elevations of 50 m) discharges from the unconfined aquifers by subsurface flow into river pools, by evapotranspiration and discharge via the river catchments to the coast (Johnson & Commander 2006). In the southern Mid-West, groundwater levels are highest following winter in September-October and lowest following summer in March-April (Wetland Research and Management 2005), with inter-annual variability related to rainfall (Clarke & Eliot 1987). Further north, there is greater inter-annual variability in groundwater levels related to rainfall activity associated with tropical cyclones, thunderstorms and northwest cloudbands (BoM 1998).

Higher groundwater levels can correspond with depletion of beach width (Clarke & Eliot 1987). During periods of lower groundwater levels the unsaturated sediments are more easily transported by wind, increasing the potential mobility of blowouts and sandsheets.

4.3. LOCAL MODIFICATIONS

Meteorologic and oceanic drivers of coastal processes on the Mid-West coast are described at a broad scale in Sections 4.2.1 through 4.2.6. However, the coastal response is a more complex function of the coastal morphodynamic system: which relates to the interaction of metocean forcing, the geological (sedimentological) framework and the landforms (Wright & Thom 1977). Interpretation of the landforms and geological structure may be used as a proxy to describe local scale variations in coastal processes that arise due to morphodynamic interactions.

4.3.1. Coastal Aspect

Coastal aspect determines the prevailing and dominant metocean processes to which the coast is susceptible (Section 3.3.2). The Mid-West coastal aspect is primarily controlled by the geologic framework, including the aspect and form of the ridges and reefs on the inner continental shelf and close to shore, as well as inherited structures along the coast. Large shelf structures such as the Beagle Islands Platform and Houtmans Abrolhos have had a long term influence on coastal landform development. Aspect is secondarily affected by the distribution of unconsolidated sediment that has accumulated against and over the bedrock topography during the Holocene, particularly the past 8,000 years, as a result of sea level rise and metocean processes. It is the combination of the two geologic components, the rocky topography and unconsolidated sedimentary morphology that give the coast its present day form.

The overall SSE to NNW trend of the coastline of the Study Area gives it a predominantly WSW aspect. This incorporates several components. Between North Head and Cliff Head the coast is mainly west facing with local aspect varying from SW to WNW. The variation is apparently due to the presence of rocky headlands, alongshore variation in the offshore reef topography and the presence of the Beagle Ridge. The offshore topography changes from a nearly continuous shore-parallel to a more discontinuous structure closer to shore, and the coast has a WSW aspect from Cliff Head to Nine Mile Beach. From there to Cape Burney South the coast has a marked SW aspect and is exposed to open ocean processes.

Between Cape Burney South and Glenfield Beach the offshore reefs curve in a seawardly convex arc around Point Moore (Langford 2000; Tecchiato & Collins 2011). This overall west facing coast is a major transition area for coastal sedimentation and landform development.

Tecchiato & Collins (2011) have reported a difference in the natural sources of sediment supplied to the shores north and south of the Point Moore tombolo; with a higher biogenic component derived from sea grass meadows in the inshore waters further south and a high component of reworked marine and terrestrially derived material to the north. The presence of heavy mineral and garnet sands derived from the Northampton Complex in beach sediments in indicative that fluvial processes have played a major geologic role in sediment supply to the coast north of the Greenough River, particularly between the Chapman and Hutt Rivers.

North of Glenfield the aspect changes and, with local variation it is south westerly to Broken Anchor Bay where Pleistocene or older topography forms a broad salient impounding the Hutt Lagoon. This salient feature has three changes in aspect: SW from Broken Anchor Bay to Eagles Nest; WSW from there to Shoal Point; and NW to Bluff Point after which the geology changes from coastal limestone to Tumblagooda Sandstone and high cliffs are present.

4.3.2. Sediment Sources

The influence of local variability in sediment supply and landform connectivity is discussed in Section 3.2. The alongshore variability in the supply of sediment from nearshore sources is significant for the landforms of the Mid-West coast, as has been demonstrated in detail by Tecchiato & Collins (2011) for the Tarcoola and Champion Bay embayments, north and south of Point Moore. It is also apparent in benthic habitat maps prepared for different sections of coast by URS (2001) and Oceanica (2008). Two sets of sediment supply are critical to the stability of unconsolidated landforms. First, the rate of onshore transport of sediment from banks, formed in the lee of reefs and islands, and seagrass meadows could undergo long-term change due to altered metocean forcing as it does with short-term changes in weather conditions such as those described by D'Adamo (1997) and Sanderson (1997). Second, supply and loss of sediment from the open coast is a function of bar opening and closing regimes at the mouths of rivers and streams, as was pointed out for South Coast Rivers by Hodgkin (1998). In this context intermittent flooding of rivers is likely to be associated with short term pulsational supply of terrestrial material to the nearshore environments adjoining their mouths as bars are overwhelmed by flood discharge. The inter-annual to inter-decadal fluctuations in sediment supply to the coast are likely to be associated with phases of dune activity or quiescence.

Along the coast south of Point Moore seagrass meadows are present largely within lagoons between the offshore reef chains and the shore, with localised patches in more sheltered areas close to cuspate forelands (DPUD 1994; MPRA 2000). The sediment produced in seagrass beds is often transported onshore across shallow banks (Figure 4-29) such as the Beagle Island Ridge between Coolimba and South Illawong (Cells 14 & 15). The river mouths and their processes are discussed in Sections 3.3.3 and 4.2.5.

Other sources of sediment include material reworked through degradation and collapse of platforms and reefs, as well as through erosion of unconsolidated sediments from banks, beaches and dunes. Some of the bank sediments, for example close to the Chapman River

(Tecchiato & Collins 2011), have been terrestrially derived and may result from stream deposition during glacial phases of lower sea level.

4.3.3. Reef Structure

The structure and formation of landforms along the shore is strongly tied to the nearshore (<20m local depth) reef systems of the Mid-West coast (Section 3.3.1; Table 3-2). The water level, waves and currents interact with the rock to modify the inshore processes, including sediment transport at all time and space scales.

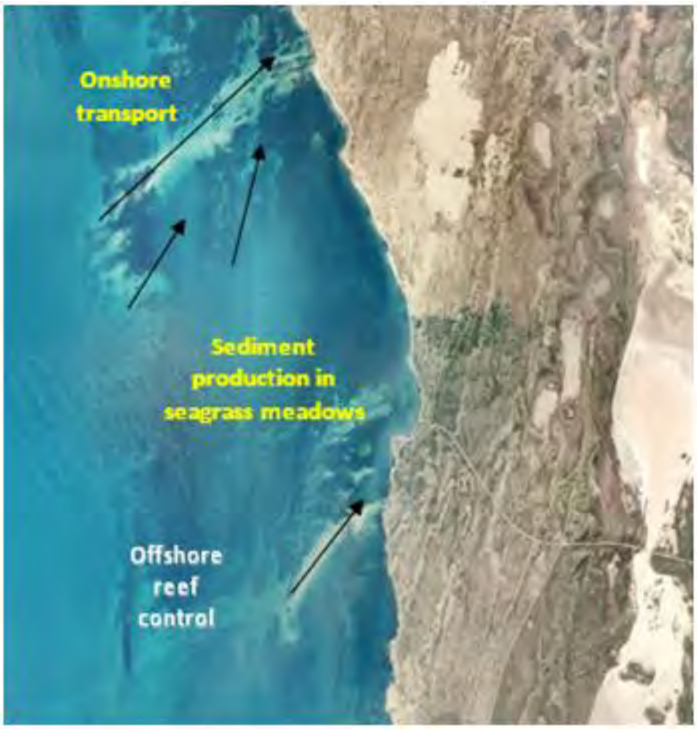


Figure 4-29: Illustration of Sediment Supply by Seagrass Meadows and Banks (Image source: Beagle Islands Orthophoto 1838. July 2006)

The degree of protection provided by reef is strongly affected by the wave conditions and the still water level (GEMS 2005). However, there is further variability associated with wave period, wave direction and the reef structure. There is often greater effectiveness of reef sheltering on the inshore wave climate during lower water levels. For low water conditions, where the reef is emergent or partially emergent, waves break at the outer edge and may possibly spill across the platform. The change in wave angle across the reef is likely to be greater for lower water level conditions. Under high water conditions lower friction is experienced. Storm erosion in many sections of the Mid-West coast will be most significant when high water levels coincide with high wave energy events, as the wave energy will transmit across the reef (CZM & Damara WA 2008). Potential future changes in amplitude and duration of water level fluctuations could alter the inshore wave climate and sediment transport, along with migratory secondary and tertiary sediment cell boundaries.

Reefs have influence on the inshore wave climate and landforms via:

- The reduction of wave energy through friction and wave-breaking. The reduction in wave transmission is dependent on reef structure, with an exponential decay in wave energy with increasing shelf width (Fredsoe & Deigaard 1992). Greater wave energy can be transmitted during higher water levels. Local wind waves will have more influence in areas where the reef protects the coast from incoming swell;

- Refraction and diffraction (islands or lumps) which alters the wave direction;
- Creating a differential in water level at the coast owing to the discontinuous structure of the reefs. Higher water levels will occur in areas with greater wave transmission, such as gaps in the reef or lower reef sections, as a result of greater wave setup. This generates alongshore currents, with sediment transported away from the areas of highest wave transmission. This mechanism contributes to the presence of sedimentary accumulation landforms adjacent to gaps in the reef (Hearn *et al.* 1986; Sanderson 2000);
- Islands which reflect and break waves with a wave shadow formed in the lee, in addition to the primary influence of wave diffraction. This produces a relatively lower water level behind the island, generating alongshore currents with sediment transported to the wave shadow area; and
- Altering the sediment transport dynamics and sediment holding capacity of beaches perched on rock (see Section 4.3.5).

Reefs and islands also contribute to the formation and amplification of currents, which influence local sediment transport rates and pathways. Wave-generated rips are repeatedly developed in gaps through relatively continuous reef sections, providing potential to transport sediment offshore (Hearn *et al.* 1986). Wind-driven flows can be accelerated through a constrained gap in the reef, or vertically over a broad reef platform. Current amplification between reefs or islands and the land (e.g. cuspate forelands) can result in locally enhanced alongshore sediment transport, contributing to the northward skewness of sedimentary accumulation landforms on the Mid-West coast (Sanderson 2000; Section 4.3.4).

Potential response of the coast to future changes in water level and wave climate (including direction) will not be uniform due to the varied reef and lagoon structures. For example, at the sub-decadal timescale the most susceptible reaches are likely to be in close proximity to salients (Section 4.3.4) and extensive rock outcrops (Section 4.3.5). Any future response to changing environmental conditions should also be superimposed on the potential for reef collapse as the Mid-West coast reef is degrading (Sanderson 2000).

Any local coastal processes investigations for the Mid-West coast require consideration of reef influence on the inshore wave climate, currents and local patterns of sediment transport in response to reef and shelf variability. The inshore non-directional wave climate has been compared to offshore non-directional wave climates for short durations for three locations of the Mid-West coast: Ledge Point (south of the Study Area; 2002-2004), Port Denison (1974-1976) and Geraldton (1984). In addition, further inshore wave monitoring has been conducted at Oakajee. The relationships interpreted from short datasets are dependent on the monitoring period in relation to the natural variability of the wave, wind and water level climates and do not necessarily capture the full range of conditions occurring at the inshore sites.

Numerical wave modelling has also been conducted at Geraldton, Oakajee and Kalbarri. However, model accuracy is strongly dependent on representing the reef structure with sufficient resolution.

4.3.3.1. Ledge Point

A wave study in the vicinity of Ledge Point, south of the Study Area, in 2002-2004 investigated the influence of reef structure on the inshore wave climate (Damara WA 2005). Relatively short periods of measurement were undertaken at four inshore locations using an AWAC meter (Table 4-16), to be compared with an offshore data set (summarised in Eliot *et al.* 2012a). Primary assessment of the data sets showed a very high correspondence of inshore and offshore wave measurements, with the inshore significant wave height typically 30-40% of that recorded offshore (Table 4-16). These results are similar to the findings of Steedman (1977) that suggested the multiple lines of reef and the beach at Mullaloo attenuated a mean 39% (range 23-71%) of the wave energy, with a standard deviation of 10%.

The inshore total wave height averaged 34% of the offshore total wave height, reaching up to 55%. There did not appear to be any clear dependence of these ratios with offshore wave height, with influence of wave period, wave direction, water level and reef structure having varied impact on the ratios.

The AWAC wave measurements showed a slightly higher level of variability between consecutive measurements compared with the waverider buoy observations. The relative contribution of instrumentation effects or inshore wave character is uncertain. However, this variability needs to be considered when comparing singular observations of offshore and inshore waves.

Table 4-16: Summary of Four AWAC Deployments at Ledge Point (Source: Damara WA 2005)

Location	Location 1	Location 3	Location 4	Location 5
Observation Period	Late Summer to Early Autumn	Late Winter to Early Spring	Late Spring to Summer	Late Summer to Autumn
Observation Dates	31/1/2003-2/4/2003	7/8/2003-2/10/2003	7/9/2003-13/2/2004	25/2/2004-19/5/2004
Storm Characteristics	No Strong Storms	4 Winter Storms	No Strong Storms	3 Autumn Storms
Water Level Effects	Weakly apparent	Apparent	Not Apparent	Apparent during storm
Mean Inshore vs Offshore (maximum)	41% (65%)	32% (50%)	28% (50%)	34% (55%)
Apparent Relationship		Depth Limited	Sensitive to Direction	

4.3.3.2. Dongara/Port Denison

The wave climate at Port Dension was investigated prior to the construction of a fishing boat harbour at Port Denison in 1979 by the Public Works Department (PWD 1976). For this investigation relatively short waverider buoy deployments (see Table 4-8 and Figure 4-1) were installed offshore (20m depth) to monitor typical ocean waves before they were attenuated by the offshore reef system and closer to shore (14m and 8m depth) to record waves typical of those that would reach the proposed breakwater and to measure the extent of wave attenuation afforded by the offshore reef.

Wave heights recorded during a storm between 28-30 the July 1975 show a reduction in wave height approximately in the range 50-75% at Location 4 (14m) with respect to Location 2 (20m; Figure 4-30). Additionally they found smaller height waves are more attenuated than larger height waves by offshore reefs, suggesting that larger waves approach from a wave direction where the offshore reefs cause the least attenuation between locations, i.e. from a westerly direction.

Offshore directional wind and swell wave data from shipping reports over the period 1952-1974 were recorded for the wider area (27°S to 31°S and 111°E to 115°E). These observations were also considered at Geraldton in DMH (1988). It was observed that the wave orthogonals tended to align perpendicular to the depth contours as the waves approach the offshore reef systems (PWD 1976).

4.3.3.3. Geraldton

A wave measurement programme in the 1980s was undertaken by the PWD in the vicinity of the Port of Geraldton, largely for consideration of Port and navigation channel dredging requirements (Steedman Limited 1985; DMH 1988). The programme consisted of four waverider buoys (see Figure 4-1 and Table 4-8) ranging from 6m depth at Location 20 and 27m depth at Location 18.

Steedman Limited (1985) fitted linear regressions to simultaneously record significant wave heights offshore at Location 18 and onshore at Locations 19 and 20 (Figure 4-31). These showed wave attenuation over the Point Moore reef system with an approximate 70% and 50% average reduction in wave heights from Locations 18 to 20 and Locations 18 to 19, respectively. It was also found that the effects of wave breaking and friction were more dominant in the larger waves.

Nearshore wave characteristics were estimated for the physical model study and the design of coastal structures phase of the *Geraldton Foreshore Development Study* (DMH 1988). This was done by mathematical modelling the refraction, shoaling and attenuation due to seabed friction and calibrated against the PWD deployments.

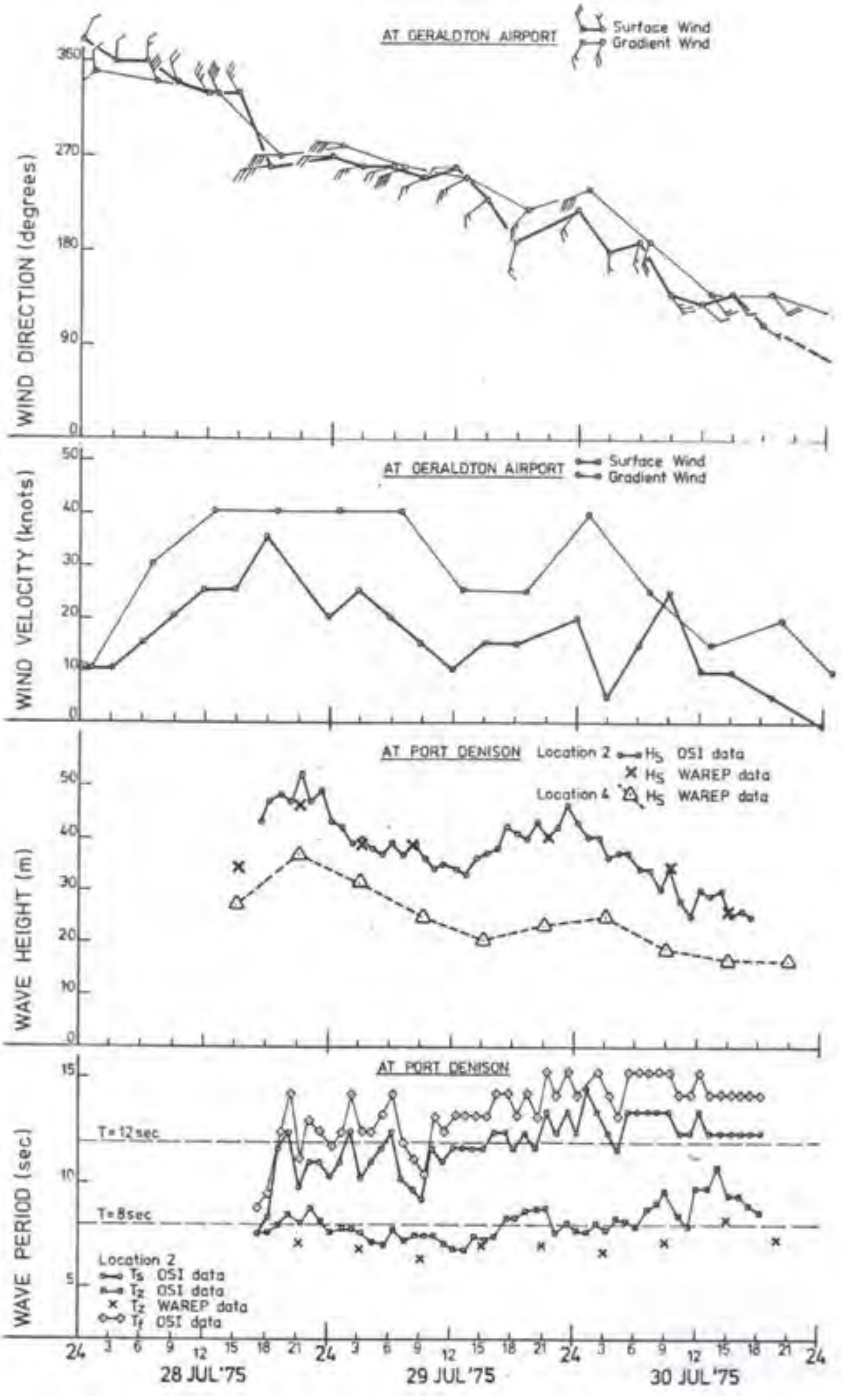


Figure 4-30: Comparison of Waves at Port Denison Locations 2 and 4 for July 28-30 1975 (Source: PWD 1976)

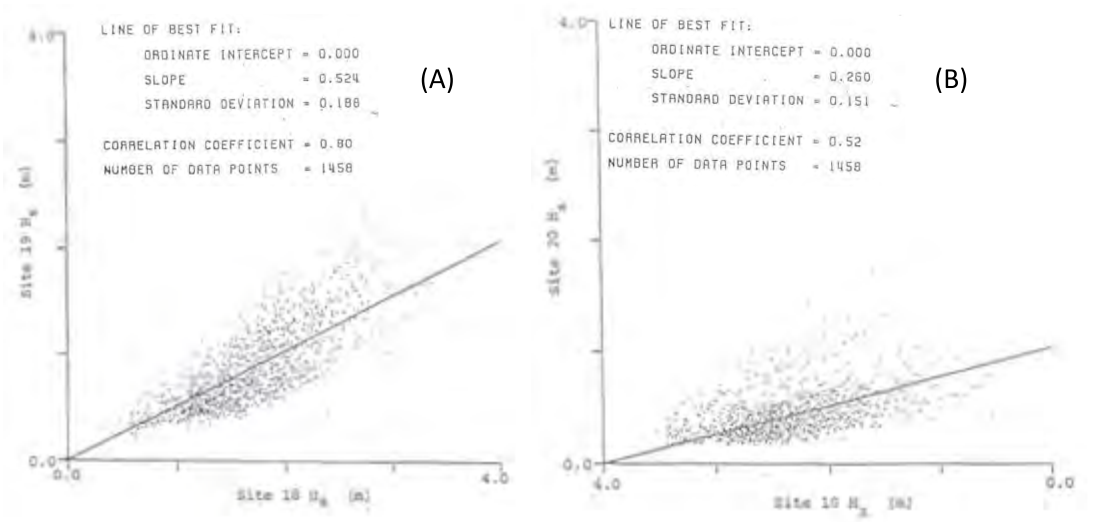


Figure 4-31: Comparison of Geraldton Wave Dataset in 1984 for (A) Locations 20 and 18 (B) Locations 20 and 19 (Source: Steedman Limited 1985)
Note: The values on the horizontal axis in figure (B) should be reversed.

4.3.3.4. Oakajee

Short term nearshore wave measurements have occurred at Oakajee from 1998 to 2000 (non-directional for Department for Planning and Infrastructure) and 2006 to 2007, and 2007 to 2008 (both directional datasets collected for Oakajee Port & Rail by RPS Metocean Engineers) (see Table 4-8 and Figure 4-1). These datasets have been summarised in Damara WA (2009) and comparison of median significant waves height with longer-term deployments in the Mid-West region show Oakajee wave measurements to be lower than Jurien Bay (depth difference) and higher than Geraldton, as less sheltered (Table 4-17).

Table 4-17: Comparison of Oakajee Wave Measurements with Jurien Bay and Geraldton

Location	Depth	Period	Median H_s (m)
Oakajee	18m	June 1998 to December 2000	1.45
Oakajee	12m	June 2006 to January 2007	1.24
Oakajee	20m	November 2007 to July 2008	1.17
Geraldton	12m	March 1999 to December 2006	0.88
Jurien Bay	42m	January 1998 to December 2009	2.2

Data from these deployments have largely been used for calibration against two longer-term modelled hindcasts (Table 4-18) generated for the development of design criteria and estimation of sediment transport for Oakajee port design. Verification was reviewed by Damara WA (2009).

Table 4-18: Modelled Hindcasts

Source	Period	Notional Water Depth
RPS MetOcean (2006)	January 1987 to December 2006	20m
GEMS (2009)	January 2001 to May 2008	20m

4.3.3.5. Kalbarri

Wave information in the Kalbarri region is limited largely to non-calibrated hindcast data developed by Oceanroutes Australia (1989) and Bailey (2005). Oceanroutes Australia (1989) developed two hindcasts, one year of modelled offshore deepwater wave conditions in 1984 centred on 28°S at the 100m depth contour and shorter period waves generated by local winds for a shallow water site approximately 3 nautical miles offshore from Kalbarri. Due to the nature of the model presentation, comparisons with other locations in the Mid-West cannot be made. This data has been used mainly to estimate littoral drift along the Kalbarri coastline) as part of investigations focused on maintaining vessel access for Kalbarri to meet the needs of the commercial fishing industry (CIES 1996; DMH 1989).

Bailey (2005) modelled the nearshore wave climate for the year 2004 to determine the likely direction of longshore sediment transport at the dredge spoil disposal sites. A median significant wave height of 1.5-2m was reported without specification of depth.

A short period of wave measurements was collected at Kalbarri, circa 1995, for determining littoral drift rates (Oceanica 2010; Matt Eliot *pers comm.*).

4.3.4. Cuspate Forelands

Salients, cuspate forelands and tombolos are common sedimentary accumulation features along the Mid-West coast south of Geraldton (Searle & Semeniuk 1985; Sanderson & Eliot 1996). They are apparent as smaller landforms in the lee of nearshore reefs in the northern part of the Study Area, between Broken Anchor Bay and Waygoe Well, where they appear to be more transient in form. Salients are low-amplitude, seawardly convex reaches of coast. As do cuspate forelands, salients occur in the lee of different reef structures. However, cuspate forelands are promontories that project well seaward from the general trend of the shoreline, often at a point of convergence of waves and currents. In this report they are commonly used to identify the boundaries of sediment cells. Tombolos extend seaward to attach to an island or reef. The initial formation of these features largely occurred during periods of different mean sea levels within the Holocene (Woods & Searle 1983; Searle *et al*. 1988), with extensive modification by contemporary metocean forcing. Cuspate forelands are included in the assessment of vulnerability for their susceptibility (Section 3.3.2) to changing metocean conditions; however, each cuspate foreland should be considered independently of the adjacent cells as each will often be more vulnerable to future environmental change.

The varied development of sedimentary accumulation landforms on the Mid-West coast is attributed to the complex reef structure, localised nearshore processes and sediment availability. There is a marked difference between the extensive depositional landforms south of Geraldton and the smaller landforms to the north where sediment supply is apparently less. More erosional landforms are apparent in the northern sector. Five types of sedimentary accumulation forms on the Central West Coast south of Geraldton have been identified by Sanderson & Eliot (1996) and are shown schematically in Figure 4-32, together with their alongshore distribution. The smaller forms of the north are not well described. Some of the landforms are migratory. Nearly all cuspate forelands are skewed in the prevailing wind-direction. They are influenced by wind-driven, circulation and local enhancement of currents between the landform and the reef or island and alongshore sediment transport by breaking wind waves, wind-driven currents and aeolian transport.

The formation and migration of salients, cuspate forelands and tombolos is potentially reversible under changing metocean and sediment supply conditions. There may be a tipping point of landform erosion that results in rapid retreat that is likely to be irreversible across the planning timeframe of 100 years. This could occur as a result of a loss of reef control (e.g. partial collapse), as has occurred at Post Office Beach in South Australia (Fotheringham 2009) and/or a significant reduction in sediment supply. There is evidence of wholesale retreat of cuspate forelands, larger in size than Island Point at Jurien Bay, in the vicinity of the Beagle Islands.

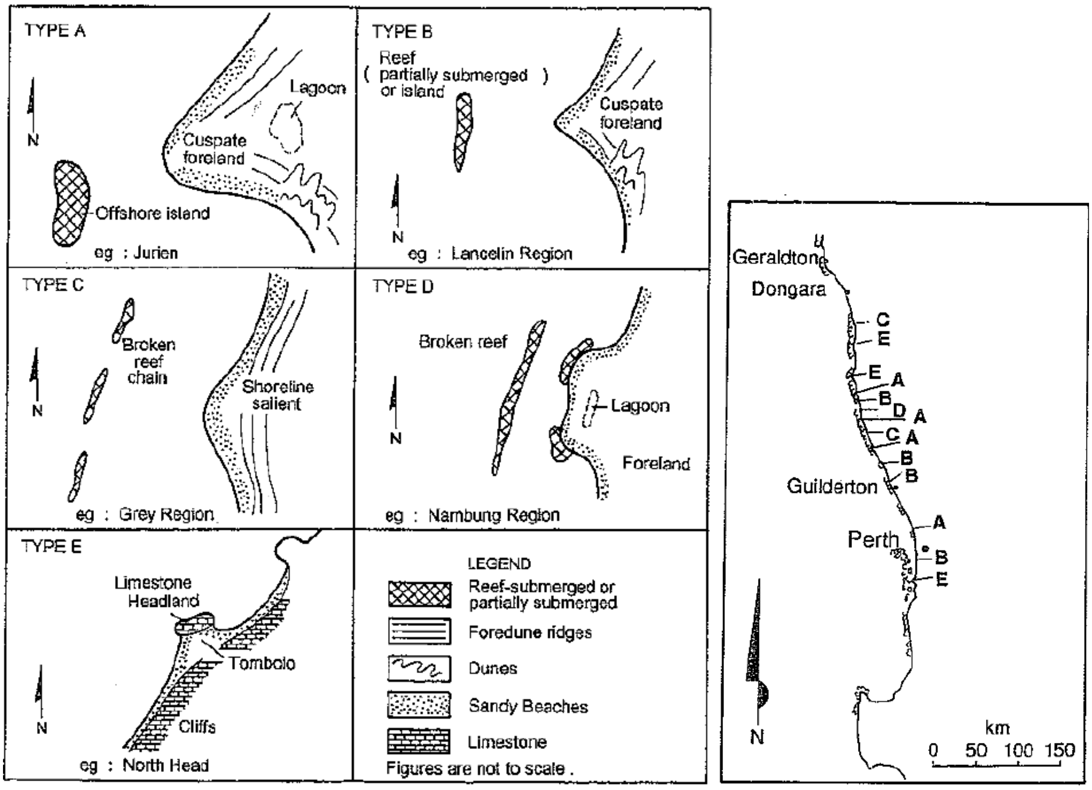


Figure 4-32: Reef Protected Features on the Central West Coast (Source: Sanderson & Eliot 1996)

4.3.5. Cliffs and Perched Beaches

Cliffs are important features of the Mid-West coast. They are significant elements of the landscape, particularly where they are high and provide vantage points along the coast, and because they commonly occur on headlands which are the control points for shoreline configuration. High sandstone cliffs are a feature of the coast at White Cliffs (Cell 52), Menai Cliffs (Cell 53) and along the coast between Bluff Point and the Murchison River (Cells 61 to 63). The cliffs and platforms cut into them are geologically old. For example Scott and Johnson (1993) have described the landforms from Jaques Point immediately north of Red Bluff, in Cell 63. They identified an approximately 100,000 year-old Pleistocene rocky shoreline with a wide variety of deposits preserved unconformably against the Tumblagooda

Sandstone of Silurian age sandstone. In places modern sands of Holocene age are mixed with the older sediments and abut cliffs or overly platforms. Further south the Pleistocene coastal limestones commonly have cliffs and platforms cut into them, for example at Point Louise and on headlands along the coast between Bat Cave Cove and Cliff Head.

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

A perched beach may be defined as an accumulation of unconsolidated sediment atop rocky coastal topography (Larson & Kraus 2000; Doucette 2009; Gallop *et al*. 2011). Semeniuk and Johnson (1985: 233) described such beaches as '*rocky shore with sandy beach*' and noted they permanently have '*a wedge, pockets or continuous ribbon of beach-dune sand overlying inner parts of the platform, notch, high tidal seacliff, supratidal seacliff and bench*'. At the broadest scale they may form the mainland barriers described by Roy *et al*. (1994). The beaches are geologically controlled, with the interaction between the local metocean processes, available sediment and underlying rock structure governing the beach response. They can undergo rapid changes in width and elevation, partially due to the restricted volume of sediment available for transport. Perched beaches are included in the assessment of vulnerability (Sections 3.3.2 and 3.3.3) but also should be considered n further detail in any local assessment.

An understanding of the perched beach system is required for assessing vulnerability on a local scale. The behaviour of perched beaches is not well described in available literature (Green 2008); however, there are some conceptual models available that describe the behaviour of certain types of perched beaches (Green 2008; Gallop *et al.* 2011). Many of these models consider cross-shore processes, such as those shown in Figure 4-33. Sediment can be contributed to the beach during low water levels when waves overtop the offshore limit of the rock platform, depositing sediment on the platform. Erosion of the beachface occurs owing to lower wave energy attenuation during high water levels, with sediment deposited seaward of the platform. These beach systems are sensitive to inter-decadal variability in metocean processes, such as periods of higher water levels removing sediment from the beachface.

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

Further consideration is required into other factors controlling the beach presence and variability, particularly the role of alongshore transport. This includes the planform behaviour of the area, such as any local currents transporting sediment beyond the platform through gaps in reefs or rips and limits to sediment availability by headlands, cliffs and engineered structures. Investigations are required into the sediment transport patterns at the site including: pathways for sediment supply and loss; the episodic erosion patterns (e.g. there may be a storm threshold for erosion); and the disjunction between the erosion and recovery processes (Figure 4-33). On parts of the coast, as at Lucys Beach there the perched beaches include a line of boulders likely to have been deposited during extreme storm conditions.

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

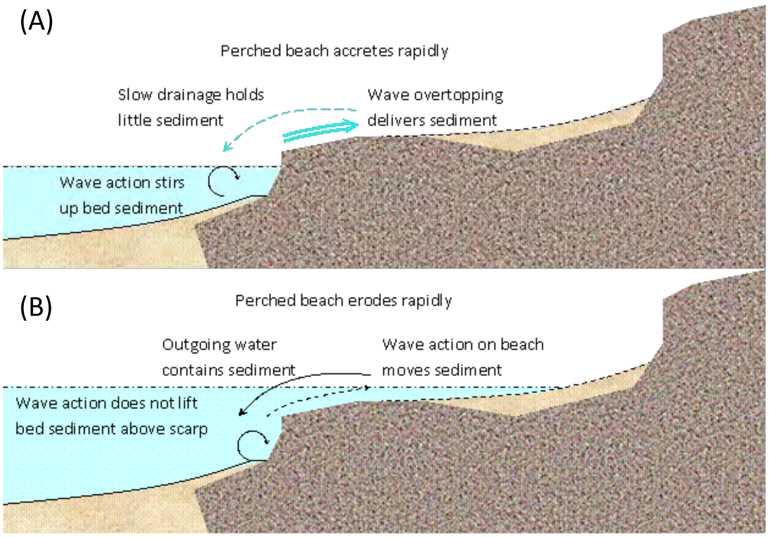


Figure 4-33: Perched Beach (A) Accretion Process and (B) Erosion Process

4.4. COASTAL CHANGE

Coastal change occurs over a wide range of temporal and spatial scales. More slowly varying metocean processes provide extrinsic forcing and affect the physical structure of the coast, whereas more rapidly varying processes cause fluctuations that have a reduced residual effect on structure when considered over an extended period but may have significant local affects on surficial landforms. The conceptual framework under which observed changes have been assessed commonly uses the assumption that different spatial scales will be dominated by processes acting over corresponding time scales (de Vriend *et al*. 1993; Cowell

& Thom 1994). This framework is often used to justify four distinct scalar concepts when describing coastal change:

1. At the largest (geological) scales, coastal change is dominated by eustasy (sea level movements), isostasy, tectonics, lithification and occasionally vulcanology (van de Plassche 1986). These processes determine the presence of rock, and through movement of relative sea level, may relate to large movements of the coast;
2. At 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 budgets tied to identification of large-scale sources, transport paths and sinks (Komar 1996; Rosati 2005) prompting the concept of equilibrium coastal alignment (van Rijn 1998);
3. Over short (planning) scales, large scale sinks and sources of material may be considered constant and 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.

There is a lack of detailed morphostratigraphic description and historical information describing metocean processes for the region. The following general observations about coastal change and stability have been drawn from available information, site visits and interpretation of imagery. They are discussed at the scales of coastal change described above.

At a geological timescale, the rocky landforms of secondary coastal compartments have provided topographic control for formation of the modern dune barrier as the dune ridge evolved during the past 10,000 years. Albeit slowly, barrier evolution is continuing at present as sediment is moved along and across the shore. Phases of dune activity associated with variation in the intensity and duration of metocean processes will continue to contribute to development of the dune ridge through the formation and destruction of foredunes, blowout activity and the migration of nested parabolic sand dunes. At a similar geological timescale, the reef and headland provide topographic control for the formation of sedimentary accumulation landforms, such as sand banks, salients, cuspate forelands and tombolos. These coincide with tertiary coastal compartment and primary sediment cell boundaries.

Medium time scales occurring over decades and centuries are relevant to barrier changes. In this context, dune formation and migration on the barrier is ultimately dependent on sediment supply from offshore and alongshore. At present the nett northerly alongshore component of sediment transport is critical to coastal stability and future evolution of the barrier. The ramifications are that future medium-term stability of the coast will potentially be affected by alteration of the rates of onshore sediment supply, any updrift interference with the coastal sediment transport, or modification to the reef or headland controls, as well as by natural variability and change to metocean processes. Dominance of the southerly component of governing metocean processes is contributing to the northwards migration of some of the sedimentary accumulation landforms on the coast (Sanderson 2000).

Local changes are also active over medium time scales, as any future destabilisation and landward movement of the dunes results in a loss of sand from the adjacent shore. There has been a general reduction in dune blowouts, and increase in vegetation cover, on the Mid-West coast from the 1960s to early 2000s, with a minor increase in dune activity recently. Changes in beach width largely correspond with dune and blowout activity. Sandsheets have continued to rapidly migrate north (northeast to northwest dependent on the local wind climate and topography) at varied rates with investigations of rates presently in progress by the Geological Survey of Western Australia. Some sandsheets are revegetating on the southern flank.

At sub-decadal time scales, interaction of modern metocean processes with the inherited geologic framework has two ramifications. Firstly, alongshore variation in coastal alignment, beach erosion and deposition, foredune formation and dune development occurs as a result of this interaction. The reaches of coast most susceptible to environmental change are commonly in close proximity to shoreline salients and extensive rock outcrops. Secondly, it invalidates application of the Bruun Rule (Bruun 1962) that has been widely applied in the calculation of setback to development on mixed sandy and rocky coast in Western Australia (WAPC 2003); a point made by Bruun himself in his criticism of the application of the ‘rule’ (Bruun 1983, 1988). This implies that localised estimation of shoreline change is necessary and should be linked to geophysical determination of the distribution and elevation of the underlying limestone topography supporting the barrier.

On an event scale, the response of beaches, foredunes and primary dunes to storms is localised, with the sediment transport influenced by the broad scale metocean processes along with the local influences of groundwater, coastal aspect, sediment supply and connectivity, reef structure and the underlying rock structure (Section 4.3). The rate of recovery during lower energy periods varies along the Mid-West coast, and is markedly influenced by the underlying rock structure as well as geographic variation in the location and extent of sediment source areas.

4.4.1. Shoreline Movement

Shoreline change is typically described in terms of cross-shore and alongshore sediment movement (van Rijn 1998). 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 nett alongshore transport is considered to represent slower changes, which may be evolutionary in nature. For example, from an analysis of 16 years of monthly data from Scarborough Beach, Clarke and Eliot (1983, 1987) attribute less than 5% of nett annual sediment movement to alongshore transport, despite being the major mechanism for long-term change. Although the distinction between cross-shore and alongshore transport is convenient, it is not altogether accurate. Significant alongshore transport also may occur pulsationally and over short times frames, particularly where the inshore bathymetry is complex and there is periodic supply of sediments along and offshore through reef gaps and from inshore banks and bars, as it is on the Mid-West coast. Similarly, cross-shore transport may not always have a nett zero change over years or even decades.

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

More detailed analysis of coastal change was completed for 11 Areas of Planning Interest (Section **6**). Vertical aerial photographs were examined from 1960/1965 and 2009, with further years in between for certain sites. Although a more detailed, photogrammetric analysis is required to fully quantify shoreline and dune movement, comparison of the photographs indicates change in the shoreline position is localised to areas between rock outcrops, in the vicinity of river mouths or corresponds to a northern migration of many of the salients and cuspate forelands. Sand sheets continue to migrate north, with some revegetating on the southern flank. However, the photographic record is not sufficiently frequent to pinpoint the number of phases and when each occurred. Sandsheet migration in the Mid-West is presently under investigation by the Geological Survey of Western Australia.

Overall the historic record indicates a shoreline that is variable, particularly adjacent to rocky headlands; in the vicinity of sedimentary accumulation landforms; in the vicinity of river mouths; and where there are fluctuations in dune activity owing to changes in vegetation cover. There are localised reaches of sandy shore backed by unstable foredunes and frontal dunes that are prone to blowouts.

4.5. PROJECTED FUTURE CHANGE

Analysis of the broad-scale susceptibility and stability of the Mid-West coast has primarily been conducted with reference to its geological framework and the landforms present. 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 (Intergovernmental Panel on Climate Change: IPCC 2007; Commonwealth Scientific and Industrial Research

Organisation: 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. Additionally, the complexity of the coast with beaches and forelands tied to the limestone topography requires a detailed geophysical assessment of potential landform change at local and site scales for areas where development is proposed, similar to that recommended for Cottesloe by CZM & Damara WA (2008).

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 1990). 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 (Titus *et al.* 1985; IPCC 1990). 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 (IPCC 2007; CSIRO 2007).

The best researched and reported components of projected change are temperature and mean sea level rise, associated with global warming, which are possibly the coastal parameters most amenable to downscaling. Mean global sea level rise is estimated to range from 0.3 to 0.9 m by 2090, with a smaller change of 0.1-0.5 m to 2040 (IPCC 2007; CSIRO 2007; DoT 2010). The well-espoused projected effect of a sea level rise is to cause a landward and upward translation of the shore profile (van Rijn 1998). However, for the Mid-West coast, such a movement is expected to be complicated through interaction with coastal rock features, including an increase in wave exposure due to reduced reef sheltering. The increased water level and wave exposure could cause inundation of some coastal lowlands; rotation or retreat of pocket beaches and barrier systems; alongshore migration of salients, forelands and tombolos; and increased influence of the underlying lithified basement. The complex nature of mixed sand and rock shoreline response to sea level variation has been demonstrated for the Swan Coastal Plain using palaeological evidence (Semeniuk 1996b).

Preliminary estimates of changes to 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 median 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 measured wave climate with the projected change to wind fields suggests that there would be a general decline of background swell, with a slight increase to summer winds. Section 4.2.3 contains further discussion on natural variability of wave heights. The effect on alongshore sediment transport and sediment budgets 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 rainfall. Findings of these analyses are relevant to the Mid-West coast, noting that there is an increasing contribution of sub-tropical and tropical forcing northwards. Studies include:

- Synoptic systems (Karelsky 1961; Steedman & Craig 1983; Trenberth 1991; Bosserelle *et al.* In Press; Haigh *et al* In Press)
- Wind observations (Steedman & Associates 1982; Panizza 1983; Nicholls *et al*. 2000; Damara WA 2003)
- Rainfall (Indian Ocean Climate Initiative: IOCI 2002; CSIRO 2007)
- Wave conditions (Riedel & Trajer 1978; Lemm 1996; CZM & Damara WA 2008; DoT 2009; Bosserelle *et al.* In Press); and
- Water levels (National Tidal Facility 2000; Feng *et al*. 2004; Pattiaratchi & Eliot 2008; 2010; Eliot 2010; Eliot 2011; Haigh *et al.* In Press).

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. Recent investigations into longer-term natural variability have incorporated reanalysis of modelled atmospheric pressure and winds to consider the variability of tracks of storm events that generated surge (largest 100 surge events) and swell (offshore H_s >7 m) in south-west Western Australia in the last 60 and 40 years respectively (Bosserelle *et al.* In Press; Haigh *et al.* In Press). Further discussion of variability is included for water levels in Section 4.2.2 and waves in Section 4.2.3.

Projected changes in rainfall are relevant for the influence of rivers and drains on the coast, coastal flooding as well as aeolian transport, dune stability and sandsheet migration. CSIRO (2007) projections for Perth coastal areas suggest decreasing rainfall, with an increase in summer rainfall and no anticipated change to the intensity of extreme rainfall events. These projections largely match local analyses of rainfall (IOCI 2002); however the highly variable regional rainfall could result in possible increases in frequency of high intensity precipitation events. Both projected rainfall and historic flood climates should be considered.

The influence of tropical and sub-tropical synoptic systems on the Mid-West coast is mainly developed through occasional southerly travelling tropical cyclones. These represent approximately 10% of cyclones within the Bureau of Meteorology tropical cyclone database, although they have been relatively under-represented since the 1980s. Historical variability of tropical cyclones is very high, and strongly biased through changes of instrumentation and observational techniques (Coleman 1972; Lourensz 1981; Landsea 2000; Damara WA 2008). There is evidence that cyclone behaviour is linked to climate variations over inter-annual time scales (Solow & Nicholls 1990; Nicholls 1992; Qi *et al*. 2008), which suggests a likely response to anthropogenic change (Knutson *et al*. 2001; Abbs *et al*. 2006). However, stark contrast between existing modelling studies (Abbs *et al*. 2006; Camargo *et al*. 2008; Leplastrier *et al*. 2008) suggests that the parameters controlling cyclone formation off Western Australia have not been fully resolved. This is consistent with the statement regarding global studies of cyclone behaviour:

> "*Current knowledge and available techniques are not able to provide robust quantitative indications of potential changes in tropical cyclone frequency*" (Henderson-Sellers *et al*. 1998; World Meteorological Organisation: WMO 2006).

In this situation, the effects of such uncertainty should be considered in the interpretation and projection of coastal change.

Coastal climate variation over the historic period is generally larger than the predicted anthropogenic forcing over the next 30 years (Eliot & Pattiaratchi 2007; CZM & Damara WA 2008; Bosserelle *et al.* In Press). 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 Mid-West 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.

Further detailed consideration of the natural variability and potential future changes in metocean forcing at a local scale is advised for any detailed site investigations of coastal processes for planning and development purposes, including setback assessments. The information included on the natural variability at a regional and local scale (Sections 4.2 and 4.3) should be combined with projected future change in metocean forcing.

5. Landform Stability & Susceptibility to Change

The Mid-West coast comprises four primary, ten secondary and 21 tertiary compartments (Figure 1-2 to Figure 1-4; Table 2-1). The Mid-West coast partly falls in the southern part of the Zuytdorp Primary Compartment to the north of the Study Area. The shires of the Study Area have boundaries that split primary compartments and in some cases adjacent jurisdictions share sediment cells. For example the Beagle Primary Compartment encompasses five shires (Dandaragan, Coorow, Carnamah, Irwin and City of Geraldton-Greenough), and the primary sediment cell of Glenfield to Buller (Cell 47) is split between the City of Geraldton-Greenough and the Shire of Chapman Valley (Table 2-1; Figure 1-4). At a more detailed scale, sixty four sediment cells have been identified between North Head and Nuningjay Springs Coast North (Figure 1-3; Figure 1-4; Table 2-1). Three cells, between Connell Road and the Marina at Geraldton (Cells 41 to 43) were not considered. They include Geraldton Port and engineered sections of coast.

The vulnerability of the four primary compartments has previously been considered by Eliot *et al.* (2011a) for strategic planning. The direct assessment of primary, secondary and tertiary compartments was not considered in this study, given the focus on local area planning. However, information is inferred on the compartments from the sediment cell assessments.

Sediment cells of the Mid-West coast are considered in detail at a landform scale appropriate to local area planning. The landforms for each sediment cell have been identified, mapped and described. The cell boundaries were identified and mapped in Figure 1-3, Figure 1-4 and Table 2-1. The landforms of each cell were mapped in Appendix C and described in Appendix D in relation to the susceptibility and instability criteria listed in Table 2-6.

5.1. LAND SYSTEM SUSCEPTIBILITY AND LANDFORM INSTABILITY

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

5.1.1. Land System Susceptibility

The major natural structural features of each of the 61 cells were described (Appendix D) and ranked (Table 5-1) according to their likely susceptibility to change. The overall results for the Mid-West coast reveal a substantial proportion, 39 of the 61 (64%) cells examined are moderately susceptible to change. Seventeen cells (28%) have a landform association with a low susceptibility; and five cells (8%) are highly susceptible. A summary of the three levels of susceptibility across primary and secondary compartments, the combined Mid-West coast and separately for each shire is shown in Table 5-2. A summary of the susceptibility across primary, secondary and tertiary compartments, and the sediment cells is included in Table 5-8.

Table 5-1: Susceptibility Rankings for Each Cell

Cell	Southern Boundary of Cell	Nearshore Morphology	Shoreline Configuration	Orientation	Barrier	Susceptibility Score	Susceptibility Ranking	Cell	Southern Boundary of Cell	Nearshore Morphology	Shoreline Configuration	Orientation	Barrier	Susceptibility Score	Susceptibility Ranking
64	Murchison River	4	2	5	1	**12**	**M**	32	Phillips Rd Coast	4	2	3	1	**10**	**M**
63	Red Bluff	4	4	5	2	**15**	**H**	31	Lucys	4	2	3	1	**10**	**M**
62	Pot Alley	4	2	5	5	**16**	**H**	30	Duncans Pool	4	2	3	1	**10**	**M**
61	Bluff Point	4	1	5	5	**15**	**H**	29	Flat Rocks	4	2	3	1	**10**	**M**
60	Waygoe Well	4	1	5	2	**12**	**M**	28	Headbutts	1	3	3	1	**8**	**L**
59	Waygoe Well S.	4	2	5	2	**13**	**M**	27	Shire Boundary	2	3	3	1	**9**	**L**
58	Yanganooka	4	1	5	2	**12**	**M**	26	Bookara South	3	1	3	1	**8**	**L**
57	Sandalwood Bay	4	2	5	4	**15**	**H**	25	Nine Mile Beach	4	3	3	1	**11**	**M**
56	Shoal Point	4	1	5	4	**14**	**M**	24	Seven Mile Beach	1	2	3	2	**8**	**L**
55	Eagles Nest	4	3	3	4	**14**	**M**	23	Harleys Hole	1	2	3	2	**8**	**L**
54	Broken Anch. Bay	4	2	3	1	**10**	**M**	22	Dongara North	1	2	3	2	**8**	**L**
53	Menai Cliffs	4	2	3	4	**13**	**M**	21	Leander Point	3	2	3	1	**9**	**L**
52	White Cliffs	4	2	3	5	**14**	**M**	20	S. Leander Point	3	3	4	1	**11**	**M**
51	Whale Boat Cove	4	2	3	5	**14**	**M**	19	White Point	3	3	4	1	**11**	**M**
50	Bowes River	2	3	3	1	**9**	**L**	18	Cliff Head	3	2	5	1	**11**	**M**
49	Coronation Beach	4	2	3	4	**13**	**M**	17	N. Knobby Head	2	1	5	1	**9**	**L**
48	Buller	4	3	3	1	**11**	**M**	16	South Illawong	2	1	5	1	**9**	**L**
47	Glenfield	4	4	5	1	**14**	**M**	15	Gum Tree Bay	1	1	5	1	**8**	**L**
46	Chapman	4	3	3	1	**11**	**M**	14	Coolimba	1	1	3	1	**6**	**L**
45	Saint Georges	3	2	5	1	**11**	**M**	13	Tailor Bay	1	1	5	1	**8**	**L**
44	Marina	3	3	5	5	**16**	**H**	12	Leeman	1	1	5	1	**8**	**L**
43	Geraldton East	Not assessed						11	Webb Islet	2	1	5	1	**9**	**L**
42	Geraldton West	Not assessed						10	unsurveyed point	2	2	5	1	**10**	**M**
41	Connell Road	Not assessed						9	Little Anchorage	2	4	5	1	**12**	**M**
40	Pages	4	3	4	2	**13**	**M**	8	Point Louise	3	2	5	1	**11**	**M**
39	West End	4	2	4	2	**12**	**M**	7	Greenhead	3	3	5	1	**12**	**M**
38	Point Moore	2	3	5	2	**12**	**M**	6	South Bay	3	3	3	1	**10**	**M**
37	Separation Point	4	3	2	2	**11**	**M**	5	Fisherman Islands	2	1	5	1	**9**	**L**
36	Cape Burney N.	4	3	4	1	**12**	**M**	4	South Fisherman	2	1	5	1	**9**	**L**
35	Greenough N.	4	2	5	1	**12**	**M**	3	Sandy Cape	3	3	4	3	**13**	**M**
34	Cape Burney S.	4	4	5	1	**14**	**M**	2	Sandland	2	3	5	4	**14**	**M**
33	West Bank	4	2	3	1	**10**	**M**	1	North Head	2	3	5	2	**12**	**M**

Sediment cells have low susceptibility where the coast is protected by a nearly continuous offshore reef or a wide shelf, platform or bank; straight or seawardly convex rocky coast; the coast is sheltered from metocean forcing; beaches are perched on an intertidal rock surface;

and/or the dune barrier is either perched on a rock surface above the highest astronomic tide or is an episodic, transgressive barrier. Tracts of land having low susceptibility are most common south of Flat Rocks (Table 5-1; Table 5-2). They occur between South Fisherman and South Bay (Cells 4 & 5), Webb Islet to Cliff Head (Cells 11 to 17), Leander Point to Seven Mile Beach (Cells 21 to 24), Bookara South and Headbutts (Cells 26 to 28) and immediately north of the Bowes River (Cell 50). These are areas where the coast is protected by offshore reef, rock typically outcrops along the shore and the dune barrier is likely to be perched on a rock surface above High Water Level.

Sediment cells considered highly susceptible to change due to unconsolidated landforms, lack of bedrock support and exposure to metocean forcing are not common in the Study Area (Table 5-1). Exceptions occur along the Geraldton coast between the Marina and St Georges (Cell 44) as well as from Sandalwood Bay to Yanganooka (Cell 57). A more extensive tract of coast that is highly susceptible to change in the natural structure is the mainly cliffed coast between Bluff Point and the Murchison River (Cells 61 to 63).

Much of the coast classed as having a moderate susceptibility to environmental change may be affected by metocean processes. Areas that are most likely to include smaller landforms that are highly susceptible to change include reaches of coast where there is limited protection by offshore reefs; the shore is exposed to NW storms; on cuspate forelands; and where small, unconsolidated sandy barriers are inset between rocky outcrops.

Adjustment of the susceptibility ranking occurs with the scale of investigation (Table 5-8) because the proportion of coast comprising particular natural structural features, land systems and landforms changes with scale. It also highlights the need for very detailed examination of landforms and processes at local planning scales. Some of the cells have a higher susceptibility ranking when considered at a finer spatial scale than secondary compartments because the more susceptible natural structural features, such as cuspate forelands comprise a higher proportion of the coast of interest.

At a broad strategic scale the Mid-West coast has moderate susceptibility.

Table 5-2: Summary of Cell Susceptibility for Coastal Segments Including Primary and Secondary Compartments, Total Study Area and the Shires Note this is a count of cells of unequal coastal extent

Compartment		No. Cells	Susceptibility - Count and Percentage of Cells			
			L	M	H	Mode
Primary	Broken Anchor Bay to Murchison River	10	0 0%	6 **60%**	4 40%	M
	Glenfield to Broken Anchor Bay	7	1 14%	6 **86%**	0 0%	M
	North Head to Glenfield	43	16 37%	26 **61%**	1 2%	M
Secondary	Murchison River to Nunginjay Spring Coast N	1	0 0%	1 **100%**	0 0%	M
	Broken Anchor Bay to Murchison River	10	0 0%	6 **60%**	4 40%	M
	Bowes River to Broken Anchor Bay	4	1 25%	3 **75%**	0 0%	M
	Glenfield to Bowes River	3	0 0%	3 **100%**	0 0%	M
	Cape Burney South to Glenfield	10	0 0%	9 **90%**	1 10%	M
	Nine Mile Beach to Cape Burney South	9	3 33%	6 **67%**	0 0%	M
	Leander Point to Nine Mile Beach	4	4 **100%**	0 0%	0 0%	L
	Cliff Head to Leander Point	3	0 0%	3 **100%**	0 0%	M
	South Illawong to Cliff Head	2	2 **100%**	0 0%	0 0%	L
	Green Head to South Illawong	9	5 **56%**	4 44%	0 0%	L
	North Head to Green Head	6	2 33%	4 **67%**	0 0%	M
Total for Mid-West		61	17 28%	39 **64%**	5 8%	M
Shire of Northampton		16	1 6%	11 **69%**	4 25%	M
Shire of Chapman Valley		2	0 0%	2 **100%**	0 0%	M
City of Geraldton-Greenough		17	2 12%	14 **82%**	1 6%	M
Shire of Irwin		11	7 **64%**	4 36%	0 0%	L
Shire of Carnamah		4	4 **100%**	0 0%	0 0%	L
Shire of Coorow		11	3 27%	8 **73%**	0 0%	M

5.1.2. Landform Instability

Simplistically, rocky sections of coast are less susceptible to change due to metocean forcing than sandy reaches along the shore and, as a first approximation, superficial (surface) landforms of the Mid-West coast were assigned a ranking for their relative stability on a three point scale following the classification of Gozzard (2011a). They were classed as being relatively stable (Low Instability), moderately stable or unstable (High Instability) and the results indicated in Table 5-3. The procedure deals specifically with landform types but omits some composite forms, notably barriers and cuspate forelands, which are structurally significant and more apparent at a broad scale. It also neglects aspects of the coast which link morphology with coastal processes and sediments. For example unconsolidated sand dunes overlying a high bedrock surface are less prone to shore erosion but may be destabilised by other processes, and there is a close relationship between the rocky topography of the inshore waters and landforms along the shore in their lee. These aspects have led to adoption of a methodology that distinguishes the structural attributes of sediment cells along the Mid-West coast from landform instability (Table 2-6).

The present instability of landform features at a cell scale were described (Appendix D) and ranked according to their likely instability (Table 5-4). Difference between the rankings for susceptibility and instability assigned to the same cell highlight the significance of long-term versus short-term change. Overall, the estimated levels of instability for each of the cells along the Mid-West coast reveal 25 of the 61 (41%) cells examined are moderately unstable and 28 cells (46%) are of high instability. Eight cells (13%) have a low instability ranking. A summary of the three levels of landform instability across primary and secondary compartments, the combined Mid-West coast and separately for each shire is shown in Table 5-5. A summary of the instability across primary, secondary and tertiary compartments, and the sediment cells is included in Table 5-8.

Sediment cells with low instability are most common on the coast south of Cliff Head (Table 5-4; Table 5-5). They occur between Sandy Cape and Fishermans Islands (Cells 3 & 4), Unsurveyed Point and Webb Islet (Cells 10 & 11), South Illawong and Cliff Head (Cells 16 & 17), Pages to Connell Road (Cell 40) and from St Georges to the Chapman River (Cell 45). Sediment cells display low instability where the coast has a limited amount of sediment stored inshore with sheltering by inshore reefs and/or rocky pavement; sandy beachface is has a sheltered profile; the frontal dune complex is relatively intact; and/or the barrier dunes are well vegetated.

Tracts of coast considered to have high instability are between Cliff Head and Leander Point (Cells 18, 19 & 20), Nine Mile Beach and Headbutts (Cells 25, 26 & 27), Duncans Pool to Cape Burney South (Cells 30 to 34) and from Bowes River to Red Bluff (Cells 50 to 62). Several isolated cells have landforms with a high level of instability. These include Cells 37, 44, 46 and 64, with southern boundaries at Separation Point, the Marina, Chapman River and the Murchison River. Combinations of some of the following factors indicate current levels of high landform instability: the inshore seabed is bare sand; beaches are commonly subject to high wave conditions or part of a barred river mouth; there is no foredune and the frontal dune is scarped; and vegetation cover is low and /or mobile sand sheets are present on the barrier.

Table 5-3: Mid-West Coast Landforms and their Relative Instability (Source: Gozzard 2011a). See Table 2-10B for Explanation of Colour Codes

Landform	Description	Relative Instability
Beach	Unconsolidated marine sediments, commonly sand and shell debris, deposited at the shore through the interaction of water levels, waves and currents.	High (Unstable)
Foredune	A single ridge or line of small dunes at the landward margin of the beach. Foredunes are the first stage of dune formation. They support pioneer vegetation communities.	High (Unstable)
Foredune Plain	Low lying plain comprising a series of relic foredune ridges aligned parallel to the coast and adjoining the active foredune; relief is commonly less than 5m.	Moderate
Active parabolic dunes and blowouts, Quindalup Dunes	U-shaped, transgressive lobes or sand sheets migrating landwards. They vary in relief from 5 to 15m close to shore with slopes of up to 50% on the advancing slip-faces.	High (Unstable)
Parabolic and nested parabolic dune complexes, Quindalup Dunes	Phases of dune development have resulted in the most recently formed dunes overriding older dunes to landward. This forms a field of nested forms with a relative relief of 20 to 40m, elevations of up to 70m and steep, unstable slopes to landward.	Moderate
Older dunes, Quindalup Dunes	Well vegetated parabolic and nested parabolic dune complexes, commonly with more subdued relief than the younger forms.	Moderate
Older deflated dunes, Quindalup Dunes	An area of low relief, commonly less than 2m, formed on Quindalup Sands	Low (Stable)
Long walled parabolic dunes Quindalup Dunes	Parabolic or U-shaped dunes with long trailing arms. These are a subset of the parabolic dunes described above and are sometimes referred to as hairpin dunes. The advancing head of the dune may be an active sand sheet.	Moderate
Deflation basins	Level to gently undulating plain bounded by the trailing arms of long-walled parabolic dunes and blowouts. The deflation basin may contain low dunes, less than 5m high with subdued relief.	Low (Stable)
Deflation basins, calcarenite floor	Level to gently undulating plain bounded by the trailing arms of long-walled parabolic dunes and blowouts. The deflation basin may contain low dunes, less than 5m high with subdued relief. The basin floor is developed in calcarenite.	Low (Stable)
Alluvial flats	Flat, level floodplain immediately adjoining a river channel.	Moderate
Alluvial channel	Main channel of a river and associated tributaries.	High (Unstable)
Alluvial terrace	High level floodplain or remnant floodplain of a river	Moderate
Alluvial fan	Level to gently inclined fan-shaped deposit at the downstream extent of a gully	Moderate
Valley flats	Small, gently inclined to level flat at the bottom of a narrow valley enclosed by steep slopes.	Moderate
Estuarine flats	Small estuarine area at the junction of a river and the ocean where stream flow is modified by tides and waves.	High (Unstable)
Lacustrine flats	Level landform of extremely low relief formerly occupied by a lake but now partly or completely dry.	Moderate
Lagoons and swamps	Overbank basins intermittently holding floodwater on the alluvial flats or terrace	Moderate
Lagoons and swamps, younger	Circular to elongate, topographically low, closed depressions, often the sites of small brackish to saline lakes	Moderate
Lagoons and swamps, older	Deposits of former inshore lagoons formed about 3000 –6500 years ago when sea level was approximately 5m higher than today.	Moderate

Landform	Description	Relative Instability
Cliff-foot slope	Parallel slopes immediately below a cliff resulting from the deposition of collapsed material from the cliff admixed with colluvial material.	Moderate
Colluvial footslopes	Moderately to very gently inclined slopes resulting from the deposition of mass wasting deposits.	Moderate
Colluvial slopes, lateritic sands and gravels	Moderately to very gently inclined slopes resulting from the deposition of lateritic sands and gravel by mass wasting.	Moderate
Colluvial slopes, sand	Moderately to very gently inclined slopes resulting from the deposition of sand by mass wasting.	Moderate
Talus slope	Moderately inclined to steep waning lower slope, consisting of rock fragments deposited by gravity	Moderate
Barrier complex: Spearwood Dune System – calcarenite	Marine and aeolian sediments lithified to form the coastal limestone which outcrop as inshore reefs, pavement, shore platforms, ramps underlying the Quindalup Sands	Low (Stable)
Cliffs, Spearwood Dune System	Steep cliffs and scarps developed in Spearwood Dune System coastal limestone and calcarenite outcrops.	Moderate
Degraded scarps and cliffs, Spearwood Dune System	Degraded steep cliffs and scarps developed in Spearwood Dune System coastal limestone and calcarenite outcrops.	High (Unstable)
Barrier complex: Spearwood Dune System - sand	Yellow sands which are residual deposits formed by the weathering of the coastal limestone and calcarenite outcrops.	Moderate
Cliffs, Tumblagooda Sandstone	Steep cliffs and scarps developed in Tumblagooda Sandstone.	Low (Stable)
Scarp, Cattamarra Coal Measures	Scarps and breakaways developed in Cattamarra Coal Measure sandstones, shales and silts.	Moderate
Hills and slopes, Toolonga Calcilutite	Gently inclined hillslopes developed in Toolonga Calcilutite.	Low (Stable)
Hills and slopes, Northampton Complex	Gently inclined hillslopes developed in granite and gneiss of the Northampton Complex.	Low (Stable)
Hills and slopes, Windalia Radiolarite	Gently inclined hillslopes developed in Windalia Radiolarite.	Low (Stable)
Hills and slopes, Tumblagoonda Sandstone	Gently inclined hillslopes developed in Tumblagooda Sandstone.	Low (Stable)
Hills and slopes, Kockatea Shale and siltstone	Gently inclined hillslopes developed in Kockatea Shale.	Low (Stable)
Planation surface, lateritic duricrust	Level to undulating plain mantled by lateritic duricrust.	Low (Stable)
Sandplain	Level to gently undulating plain of low relief mantled by residual sand.	Low (Stable)
Gravel plain	Level to gently undulating plain of low relief mantled by gravel.	Low (Stable)
Plateau, calcrete	Level to undulating high-level plain mantled by calcrete.	Low (Stable)
Plateau, Windalia Radiolarite	Level to undulating high-level plain mantled by Windalia Radiolarite.	Low (Stable)

Adjustment of landform rankings, in this case instability rankings, again varies with the scale of investigation (Table 5-8) because the proportion of coast comprising particular unstable landforms changes with scale. Some of the cells have a higher instability ranking when considered at a finer spatial scale than secondary compartments because the more unstable landforms, such as active dunes and scarped foredunes, represent a higher proportion of the coast of interest.

At a broad strategic scale the Mid-West coast has high instability.

Table 5-4: Instability Rankings for Each Cell

Cell	Southern Boundary of Cell	Inshore Substrate	Beachface Profile	Frontal Dune	Barrier Vegetation	Instability Score	Instability Ranking
64	Murchison River	2	5	5	3	**15**	**H**
63	Red Bluff	2	3	5	2	**12**	**M**
62	Pot Alley	2	5	5	5	**17**	**H**
61	Bluff Point	2	5	5	5	**17**	**H**
60	Waygoe Well	4	4	4	4	**16**	**H**
59	Waygoe Well S.	4	3	4	5	**16**	**H**
58	Yanganooka	4	3	4	4	**15**	**H**
57	Sandalwood Bay	4	3	4	4	**15**	**H**
56	Shoal Point	4	5	4	3	**16**	**H**
55	Eagles Nest	4	5	4	4	**17**	**H**
54	Broken Anch. Bay	4	4	4	3	**15**	**H**
53	Menai Cliffs	4	4	4	3	**15**	**H**
52	White Cliffs	4	4	3	5	**16**	**H**
51	Whale Boat Cove	4	4	5	5	**18**	**H**
50	Bowes River	4	3	4	4	**15**	**H**
49	Coronation Beach	4	3	4	3	**14**	**M**
48	Buller	4	4	3	3	**14**	**M**
47	Glenfield	3	4	4	3	**14**	**M**
46	Chapman	4	4	4	3	**15**	**H**
45	Saint Georges	3	1	2	3	**9**	**L**
44	Marina	3	3	5	5	**16**	**H**
43	Geraldton East	Not assessed					
42	Geraldton West	Not assessed					
41	Connell Road	Not assessed					
40	Pages	4	1	1	3	**9**	**L**
39	West End	4	3	4	3	**14**	**M**
38	Point Moore	4	4	1	3	**12**	**M**
37	Separation Point	4	4	5	3	**16**	**H**
36	Cape Burney N.	3	4	4	3	**14**	**M**
35	Greenough N.	3	3	5	3	**14**	**M**
34	Cape Burney S.	4	5	4	3	**16**	**H**
33	West Bank	3	4	4	4	**15**	**H**
32	Phillips Rd Coast	4	4	4	3	**15**	**H**
31	Lucys	4	4	4	4	**16**	**H**
30	Duncans Pool	4	4	4	4	**16**	**H**
29	Flat Rocks	3	3	4	3	**13**	**M**
28	Headbutts	3	3	4	3	**13**	**M**
27	Shire Boundary	3	5	4	3	**15**	**H**
26	Bookara South	3	5	4	3	**15**	**H**
25	Nine Mile Beach	4	4	4	5	**17**	**H**
24	Seven Mile Beach	3	3	3	2	**11**	**M**
23	Harleys Hole	3	3	2	2	**10**	**M**
22	Dongara North	3	3	2	2	**10**	**M**
21	Leander Point	2	3	3	3	**11**	**M**
20	S. Leander Point	5	5	4	3	**17**	**H**
19	White Point	5	5	4	3	**17**	**H**
18	Cliff Head	4	4	4	3	**15**	**H**
17	N. Knobby Head	3	1	3	2	**9**	**L**
16	South Illawong	3	1	3	2	**9**	**L**
15	Gum Tree Bay	3	1	4	3	**11**	**M**
14	Coolimba	4	1	3	3	**11**	**M**
13	Tailor Bay	3	1	3	3	**10**	**M**
12	Leeman	3	1	3	3	**10**	**M**
11	Webb Islet	2	1	5	1	**9**	**L**
10	unsurveyed point	2	2	5	1	**10**	**L**
9	Little Anchorage	2	4	5	1	**12**	**M**
8	Point Louise	3	2	3	2	**10**	**M**
7	Greenhead	3	3	2	3	**11**	**M**
6	South Bay	3	3	4	3	**13**	**M**
5	Fisherman Islands	3	3	3	4	**13**	**M**
4	South Fisherman	2	2	1	2	**7**	**L**
3	Sandy Cape	2	3	3	1	**9**	**L**
2	Sandland	3	4	3	3	**13**	**M**
1	North Head	2	3	3	4	**12**	**M**

Table 5-5: Summary of Cell Instability for Coastal Segments
Including Primary and Secondary Compartments, Total Study Area and the Shires
Note this is a count of cells of unequal coastal extent

Compartment		No. Cells	Instability - Count and Percentage of Cells			
			L	M	H	Mode
Primary	Broken Anchor Bay to Murchison River	10	0	1	9	H
			0%	10%	**90%**	
	Glenfield to Broken Anchor Bay	7	0	3	4	H
			0%	43%	**57%**	
	North Head to Glenfield	43	8	21	14	M
			19%	**48%**	33%	
Secondary	Murchison River to Nunginjay Spring Coast N	1	0	0	1	H
			0%	0%	**100%**	
	Broken Anchor Bay to Murchison River	10	0	1	9	H
			0%	10%	**90%**	
	Bowes River to Broken Anchor Bay	4	0	0	4	H
			0%	0%	**100%**	
	Glenfield to Bowes River	3	0	3	0	M
			0%	**100%**	0%	
	Cape Burney South to Glenfield	10	2	4	4	M H
			20%	**40%**	**40%**	
	Nine Mile Beach to Cape Burney South	9	0	2	7	H
			0%	22%	**78%**	
	Leander Point to Nine Mile Beach	4	0	4	0	M
			0%	**100%**	0%	
	Cliff Head to Leander Point	3	0	0	3	H
			0%	0%	**100%**	
	South Illawong to Cliff Head	2	2	0	0	L
			100%	0%	0%	
	Green Head to South Illawong	9	2	7	0	M
			22%	**88%**	0%	
	North Head to Green Head	6	2	4	0	M
			33%	**67%**	0%	
Total for Mid-West		61	8	25	28	H
			13%	41%	**46%**	
Shire of Northampton		16	0	2	14	H
			0%	13%	**88%**	
Shire of Chapman Valley		2	0	2	0	M
			0%	**100%**	0%	
City of Geraldton-Greenough		17	2	6	9	H
			12%	35%	**53%**	
Shire of Irwin		11	2	4	5	H
			18%	36%	**46%**	
Shire of Carnamah		4	0	4	0	M
			0%	**100%**	0%	
Shire of Coorow		11	4	7	0	M

5.2. VULNERABILITY

The vulnerability of the cells was estimated by combining the overall rankings for susceptibility and instability to identify the likelihood of geomorphic change, grouped into five categories (Table 5-6; Figure 5-1; Figure 5-2). Descriptions of the main natural structural features and landform instability for each cell are included in Appendix D. The overall results for the Mid-West coast indicate four (6.5%) of the 61 cells examined have a low level of vulnerability; fourteen (23%) are of low-to-moderate vulnerability; seventeen (28%) are moderately vulnerable; twenty two (36%) are of moderate-to-high vulnerability and four (6.5%) have a high vulnerability. A summary of the five levels of vulnerability across primary and secondary compartments, the combined Mid-West Coast and separately for each shire is shown in Table 5-7. A summary of the susceptibility, instability and vulnerability across primary, secondary and tertiary compartments, and the sediment cells is included in Table 5-8.

At a broad, regional planning scale, distinct landform patterns are apparent in each of the secondary compartments occurring in the Study Area, each characterising the structural compartment in which it occurs. The compartments are described in the sequence of nett littoral sediment transport from south to north and the prevailing features of each are as follows:

1. The secondary compartment between South Illawong and Cliff Head with the lowest susceptibility to change. Its vulnerability and instability rankings are both low (Table 5-7). Continuous offshore reef shelters much of the SW facing shore and much of the shoreface is shallow. Low-energy reflective beaches are inset between outcrops of rocky shore. Landward, the perched barrier is comprised of nested parabolic and blowout dunes. These are well vegetated away from the frontal dune ridge.
2. Coastal vulnerability rankings in two secondary compartments between North Green Head and South Illawong (Cells 17 to 15), and from Leander Point to Nine Mile Beach (Cells 21 to 25) have an overall low -to -moderate ranking.

   Between GreenNorth Head and South Illawong, the individual cell rankings range from low to moderate. Cells in the central part of the compartment, between South BayGreen Head and unsurveyed point, display moderate levels of susceptibility and instability, as does the coast between North Head and Sandy Cape. These are areas with a variety of landforms including cuspate forelands and tombolos as well as perched beaches and small embayments. In places, the frontal dune ridge is scarped along the shore and foredunes are either absent or discontinuous. The episodic dune barriers have small blowouts and some mobile sand sheets. There is evidence of disturbance related to vehicle access tracks.

   Sheltered beaches; most perched on rock platforms are found along the coast between Leander Point and Nine Mile Beach (Cells 21 to 25). The beaches front episodic transgressive barriers and foredune plains with high frontal dunes. The foredunes and frontal dunes have been locally scarped and cut by access tracks. The combination of a low susceptibility to change and a moderate level of instability gives the secondary compartment its overall susceptibility ranking.

3. Threewo adjoining secondary compartments have a moderate vulnerability ranking: North Head to Green Head (Cells 1 to 6); Cape Burney South to Glenfield (Cells 34 to 46) and Glenfield to the Bowes River (Cells 46 to 49). Between North Head and Green Head there are cuspate forelands, tombolos, perched beaches and small embayments. In places, the frontal dune ridge is scarped along the shore and foredunes are either absent or discontinuous. The episodic dune barriers have small blowouts and some mobile sand sheets. There is evidence of disturbance related to vehicle access tracks. The secondformer includes the shores of the Tarcoola Embayment and Champion Bay which are separated by the Point Moore Tombolo. Diversity of landform, in part underlain by coastal limestone and generally overlain by urban development in the Geraldton area has given rise to a wide range of instability rankings. High instability is notable between Separation Point and Point Moore (Cell 37) as well as between the Chapman River and Glenfield (Cell 46). The coast between the Marina and St Georges (Cell 44) is both highly susceptible to change due to its exposure and has a high instability ranking. It is a severely eroded shore.

   The character of the coast changes between Glenfield and the Bowes River. The inner continental shelf and shoreface are narrower than further south; much of the shore is stabilised by rock platforms and low bluff; the beaches are increasingly exposed with distance north; barrier forms included episodic transgressive dunes or narrow foredune plains abutting an older barrier complex; and there are numerous ORV tracks in the area. The vulnerability ranking is derived from moderate levels of susceptibility and instability in the three cells comprising the compartment.

4. The remainder of the compartments subject to an overall moderate to high level of vulnerability to environmental change. This is apparent in three geographic areas.

   First, a wide transgressive barrier with nested parabolic dunes and mobile sand sheets is present between Cliff Head and Leander Point (Cells 18 to 20). It has formed landward a sandy inshore and has exposed beaches with bars and rips along a rhythmic shoreline. In many places, the frontal dunes have been scarped and a discontinuous foredune has formed seaward of the scarp face. These characteristics indicate moderate levels of vulnerability and a high level of instability.

   Second, from Nine Mile Beach to Cape Burney South (Cells 25 to 33) much of the coast is stabilized by a high rock platform and beaches are either perched on the platform or occur in small embayments between rock outcrops. The inshore reef pattern alters and the degree of exposure increases with distance north. As a result the susceptibility of the cells in the compartment is low in the southern and moderate in the northern part of the compartment. In contrast to this the coastal barrier is high, narrow and incorporates active blowouts, mobile sand sheets, eroded frontal dunes and ORV tracks which indicate a high level of landform instability.

Third, the three compartments north of Bowes River (Cells 50 to 64) contain extensive reaches of rocky coast with cliffs and/or shore platforms. The susceptibility of cells within the compartments is mainly moderate, although the cliffed coast between Bluff Point and the Murchison River adjoins a deep inshore and is potentially highly susceptible to erosion at a seabed level. Low lagoonal shores landward of exposed linear reefs at Horrocks, Port Gregory and along the coast Eagles Nest to Waygoe Well are indicative of long-term coastal erosion and in many places the coast is backed by mobile dunes and sand sheets. Correspondingly, the compartment has a high instability ranking.

The Mid-West coast comprises three primary compartments within the South West Coast Region (Table 2-1; Figure 1-2) each with a different land system. In the northern reaches the Study Area partly extends into a fourth compartment, the Zuytdorp Compartment which includes the Zuytdorp Cliffs. The three complete compartments extend from North Head to Glenfield (Beagle Compartment); Glenfield to Broken Bay (Oakajee Compartment) and Broken Bay to the Murchison River (Hutt Compartment). They have been attributed a moderate-to-high or high vulnerability ranking based on the landforms present (Figure 5-3). For the planning purposes of this report the approach used in investigating coastal vulnerability has been extended to a finer spatial scale, to a primary sediment cell level. This has led to further consideration of the integrity of natural structures of land systems and landforms as well as their condition or stability. It results in adjustment of the vulnerability ranking because the proportion of coast comprising particular land systems and landforms changes with the scale of investigation. The overall vulnerability of the primary compartment forming most of Mid-West coast is rated as having moderate-to-high vulnerability to changing metocean processes (Table 5-7; Table 5-8).

Adjustment of the vulnerability rankings alter with the scale of investigation (Table 5-8) because the proportion of coast comprising susceptible natural structural features and/or particular unstable landforms changes with scale. Some of the cells have a higher vulnerability ranking when considered at a finer spatial scale than the secondary compartments because the areas of higher coastal risk represent a higher proportion of the coast of interest. Higher coastal risk could be attributed to a higher proportion of susceptible natural structural features, such as cuspate forelands, and/or more unstable landforms, such as active dunes and scarped foredunes.

At a more local level it is pertinent to consider vulnerability at a more detailed, cell by cell scale (Table 5-6; Appendix E). The two extreme conditions of low and high vulnerability are reviewed here. The geographic distinction between the vulnerability of the coast north and south of Geraldton apparent at a compartmental scale is highlighted when individual cells are considered. The four cells with a low vulnerability ranking (Cells 4, 11, 16 & 17) are located south of Geraldton whereas those with a high vulnerability (Cells 44, 57, 61 & 62) are located to the north (Figure 5-1; Figure 5-2).

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

1. On the coast between South Fisherman and Fisherman Islands (Cell 4) a narrow sandy beach extends along a nearly straight shore. In parts it is perched on rock platform and at one point interrupted by a rocky headland. Where not covered in wrack, the morphology of the sheltered beach is flat or rounded. To landward, long-walled, nested parabolic dunes form an episodic, transgressive barrier overlying an irregular limestone surface. The frontal dune complex is fully vegetated, and there is over 75% vegetation cover with mobile sands occurring in the northern part of the barrier.
2. The predominantly rocky coast between Webb Islet and Leeman (Cell 11) forms a shallowly indented arcuate shoreline facing WNW. Some small, shallowly arcuate sandy beaches are perched on platforms and pavement between headland outcrops. The cell largely comprises perched parabolic dunes with 25 to 75% vegetation cover overlying coastal limestone. Foredunes abutting the small beaches have been cliffed by erosion. Access tracks along the coast and to the small sheltered beaches are common.
3. A perched beach with flat to rounded profile extends continuously along the coast between South Illawong and North Nobby Head (Cell 16) and from North Knobby Head to Cliff Head (Cell 17). In places beachrock is exposed on the landward side of the beaches in both cells and the shoreline has low-amplitude salients with a shallow embayment between them.
   The barrier in Cell 16 is comprised of older parabolic dunes perched on coastal limestone which outcrops as low bluffs along the coast. The parabolic dune field terminates at the northern end of the cell. Its vegetation cover is 25 to 75% with much clearance on freehold land. A narrow foredune plain separates the limestone bluffs from the shore. Its vegetation cover varies from 25 to 75% and is substantially disturbed by ORV tracks.
4. The Holocene barrier between North Knobby Head and Cliff Head (Cell 17) is largely comprised of a foredune plain less than 200m wide. It is immediately seaward of limestone bluffs which outcrop as higher cliffs in the northern part of the cell. Some older perched dunes are located landward of the bluffs. The foredune plain has 25 to 75% vegetation cover and is eroded along its seaward margin.

Cells with a high vulnerability ranking are those with highly susceptible natural structural features and high landform instability. These are areas where coastal risk is a major constraint for coastal management. The site has major constraints due to low integrity of the natural structure, little natural resilience and high ongoing management requirements. Development at these sites should be considered highly constrained.

An exception is where large-scale infrastructure may require coastal access (eg. for marine-based industries, major harbours or port facilities). Detailed geotechnical investigation (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique), sediment budget analysis (approximate volumetric rates of sediment transport including sources and sinks) and numerical modelling (such as wave, current and sediment transport modelling to provide further context for the volumetric rates of sediment transport) are recommended as the basis for establishment of such infrastructure.

Additionally, it is recommended that planning assessment require consideration of long-term management responsibility for coastal protection and stabilisation works, as well as for ongoing maintenance and management of the site. The Department of Transport's operational policy for coastal protection (DPI 2006) indicates that the State has not provided erosion protection for private property, and has no general obligation to do so. The authority to assist local government with finance for coastal protection works is only through ministerial direction. Proposed developments should consider responsibility for protection works, or ongoing maintenance.
Landforms of the cells with an estimated high vulnerability are as follows:

1. North of the Marina to St Georges (Cell 44) a narrow, commonly <25m wide sandy beach is perched on rock platform and abuts a scarped older land-surface. The beach is eroding as is indicated by the installation of shore stabilisation works; a shore-parallel offshore breakwater and an onshore revetment. Under low wave conditions the beach is sheltered but it is exposed and higher sea levels may inundate the backshore above the platform. There is evidence of nested parabolic dunes perched on or abutting coastal limestone. However the barrier now supports urban development. Its frontal dunes have been destroyed and the foredune that originally comprised the foreshore reserve has been wholly eroded along the southern half of the cell and is in retreat along the northern sector of the cell. It is an area requiring ongoing maintenance.

2. A limestone reef and platforms outcrop intermittently close to the 5m isobath and within 200m of the shore between Sandalwood Bay and Bluff Point (Cell 57). Gaps in the reef open to small lagoons such as those at Sandalwood Bay, Halfway Bay and Lucky Bay. This section of the coast has a discontinuous, narrow rock platform extending along the shore and much the beach is separated from the reef by a lagoon up to 250m wide. The shoreline on the landward side of the lagoon is rhythmic with unvegetated salients tied to high rock outcrops in the inshore waters. The barrier is a narrow foredune plain approximately 1 to 1.5km wide with mound dunes and chenier ridges over lake sediments. North of the plain is a narrow episodic transgressive barrier on which over 75% of the surface is occupied by mobile sand sheets perched on older dunes. Frontal dunes and a foredune ridge have formed in the southern section. These have a 25 to 50% vegetation cover with small blowout dunes between mound dunes along the foredune ridge.

3. In the inshore waters between Bluff Point and Red Bluff (Cells 61 & 62) the 20m isobath is approximately 500m offshore and the seabed rises steeply to a continuous platform abutting a cliffed sandstone coast. Close to shore the seabed is mainly covered with intermittent reef. Immediately north of Bluff Point the cliffs are skirted by a wide platform, with widths ranging up to 150m. Between Pot Alley and Red Bluff the irregular sandstone cliff falls to a talus slope and deep water. There is no sandy beach or barrier on the exposed rocky coast. In the northern cell the cliff line is markedly dissected by deep gullies.

Table 5-6: Susceptibility, Instability and Vulnerability Rankings for Each Cell

Cell	Southern Boundary of Cell	Susceptibility	Instability	Vulnerability
64	Murchison River	M	H	M-H
63	Red Bluff	H	M	M-H
62	Pot Alley	H	H	H
61	Bluff Point	H	H	H
60	Waygoe Well	M	H	M-H
59	Waygoe Well S.	M	H	M-H
58	Yanganooka	M	H	M-H
57	Sandalwood Bay	H	H	H
56	Shoal Point	M	H	M-H
55	Eagles Nest	M	H	M-H
54	Broken Anchor Bay	M	H	M-H
53	Menai Cliffs	M	H	M-H
52	White Cliffs	M	H	M-H
51	Whale Boat Cove	M	H	M-H
50	Bowes River	L	H	M
49	Coronation Beach	M	M	M
48	Buller	M	M	M
47	Glenfield	M	M	M
46	Chapman	M	H	M-H
45	Saint Georges	M	L	L-M
44	Marina	H	H	H
43	Geraldton East	Not assessed		
42	Geraldton West	Not assessed		
41	Connell Road	Not assessed		
40	Pages	M	L	L-M
39	West End	M	M	M
38	Point Moore	M	M	M
37	Separation Point	M	H	M-H
36	Cape Burney N.	M	M	M
35	Greenough North	M	M	M
34	Cape Burney South	M	H	M-H
33	West Bank	M	H	M-H
32	Phillips Road Coast	M	H	M-H
31	Lucys	M	H	M-H
30	Duncans Pool	M	H	M-H
29	Flat Rocks	M	M	M
28	Headbutts	L	M	L-M
27	Shire Boundary	L	H	M
26	Bookara South	L	H	M
25	Nine Mile Beach	M	H	M-H
24	Seven Mile Beach	L	M	L-M
23	Harleys Hole	L	M	L-M
22	Dongara North	L	M	L-M
21	Leander Point	L	M	L-M
20	South Leander Point	M	H	M-H
19	White Point	M	H	M-H
18	Cliff Head	M	H	M-H
17	North Knobby Head	L	L	L
16	South Illawong	L	L	L
15	Gum Tree Bay	L	M	L-M
14	Coolimba	L	M	L-M
13	Tailor Bay	L	M	L-M
12	Leeman	L	M	L-M
11	Webb Islet	L	L	L
10	unsurveyed point	M	L	L-M
9	Little Anchorage	M	M	M
8	Point Louise	M	M	M
7	Greenhead	M	M	M
6	South Bay	M	M	M
5	Fisherman Islands	L	M	L-M
4	South Fisherman	L	L	L
3	Sandy Cape	M	L	L-M
2	Sandland	M	M	M
1	North Head	M	M	M

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

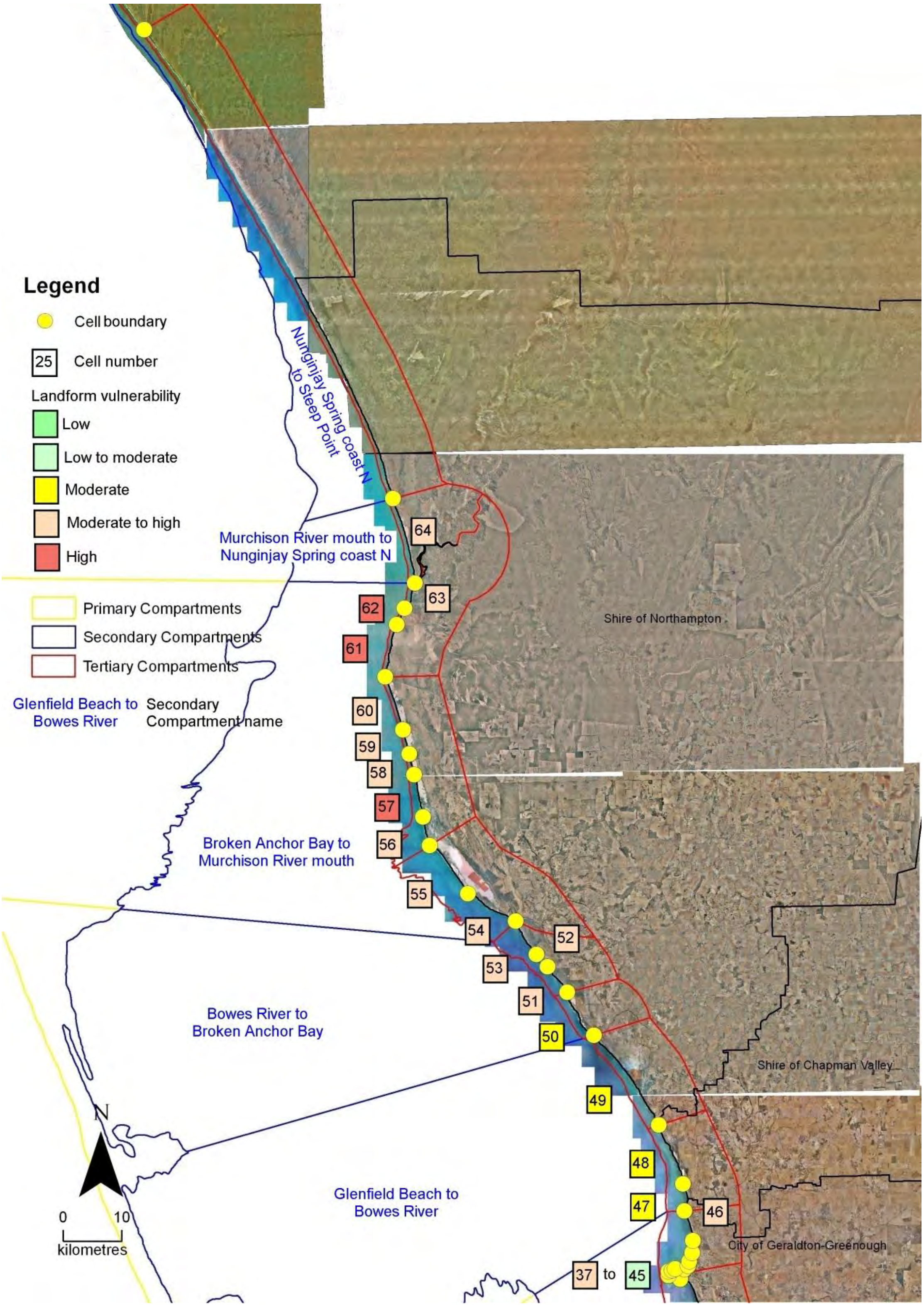


Figure 5-1: Vulnerability Rankings for the Mid-West Coast (Cells 37-64)

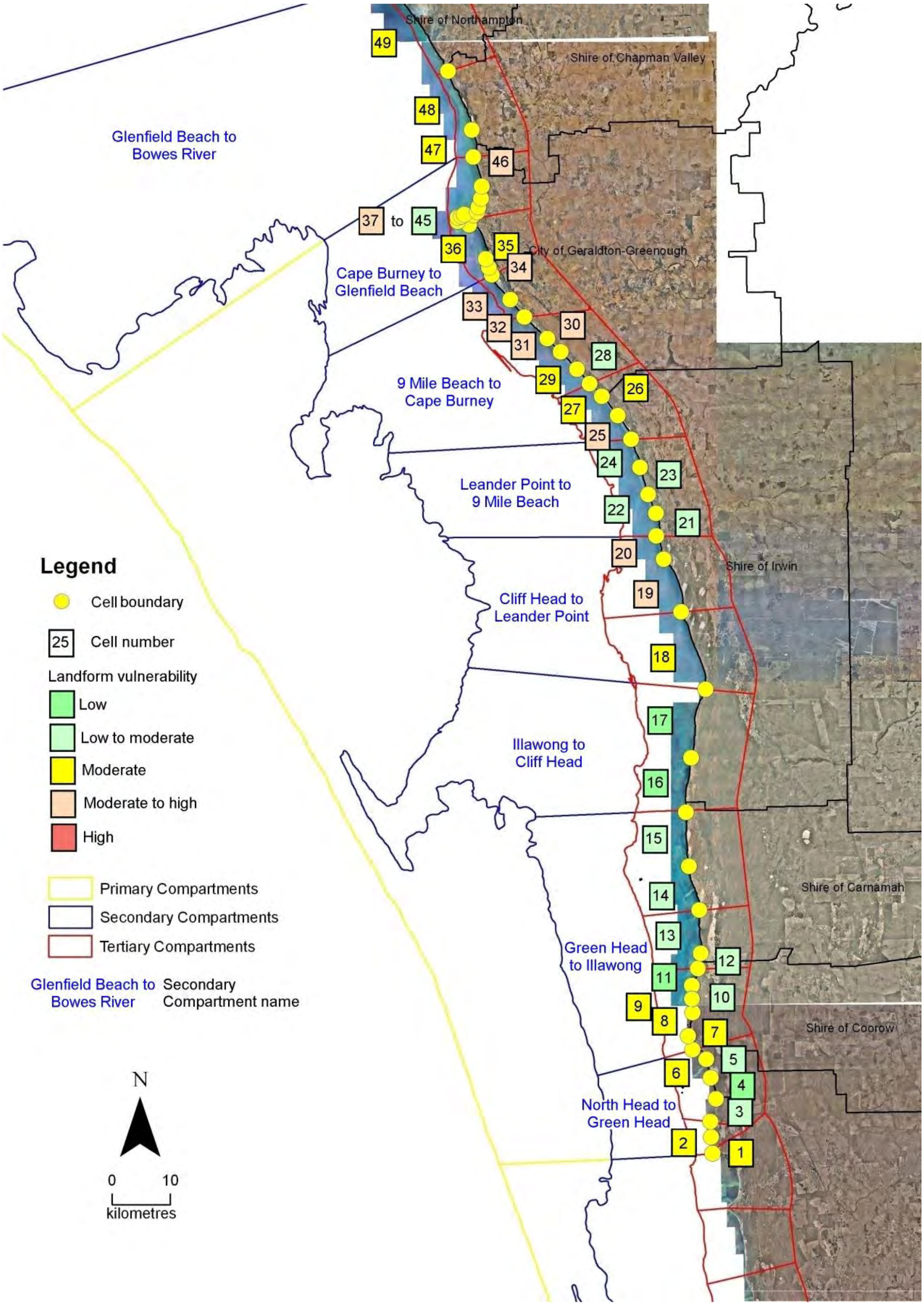


Figure 5-2: Vulnerability Rankings for the Mid-West Coast (Cells 1-49)

Table 5-7: Summary of Cell Vulnerability for Coastal Segments
Including Primary and Secondary Compartments, Total Study Area and the Shires
Note this is a count of cells of unequal coastal extent

Compartment		No. Cells	Vulnerability - Count and Percentage of Cells					
			L	**L-M**	**M**	**M-H**	**H**	**Mode**
Primary	Broken Anchor Bay to Murchison River	10	0	0	0	7	3	M-H
			0%	0%	0%	**70%**	30%	
	Glenfield to Broken Anchor Bay	7	0	0	4	3	0	M
			0%	0%	**57%**	43%	0%	
	North Head to Glenfield	43	4	14	13	11	1	L-M
			9%	**33%**	30%	26%	2%	
Secondary	Murchison River to Nunginjay Spring Coast N	1	0	0	0	1	0	M-H
			0%	0%	0%	**100%**	0%	
	Broken Anchor Bay to Murchison River	10	0	0	0	7	3	M-H
			0%	0%	0%	**70%**	30%	
	Bowes River to Broken Anchor Bay	4	0	0	1	3	0	M-H
			0%	0%	25%	**75%**	0%	
	Glenfield to Bowes River	3	0	0	3	0	0	M
			0%	0%	**100%**	0%	0%	
	Cape Burney South to Glenfield	10	0	2	4	3	1	M
			0%	20%	**40%**	30%	10%	
	Nine Mile Beach to Cape Burney South	9	0	1	3	5	0	M-H
			0%	11%	33%	**56%**	0%	
	Leander Point to Nine Mile Beach	4	0	4	0	0	0	L-M
			0%	**100%**	0%	0%	0%	
	Cliff Head to Leander Point	3	0	0	0	3	0	M-H
			0%	0%	0%	**100%**	0%	
	South Illawong to Cliff Head	2	2	0	0	0	0	L
			100%	0%	0%	0%	0%	
	Green Head to South Illawong	9	1	5	3	0	0	L-M
			11%	**56%**	33%	0%	0%	
	North Head to Green Head	6	1	2	3	0	0	M
			17%	33%	**50%**	0%	0%	
Total for Mid-West		61	4	14	17	22	4	M-H
			6.5%	23%	28%	**36%**	6.5%	
Shire of Northampton		16	0	0	2	11	3	M-H
			0%	0%	12%	**69%**	19%	
Shire of Chapman Valley		2	0	0	2	0	0	M
			0%	0%	**100%**	0%	0%	
City of Geraldton-Greenough		17	0	3	6	7	1	M-H
			0%	18%	35%	**41%**	6%	
Shire of Irwin		11	2	4	1	4	0	L-M M-H
			18%	**36.5%**	9%	**36.5%**	0%	
Shire of Carnamah		4	0	4	0	0	0	L-M
			0%	**100%**	0%	0%	0%	
Shire of Coorow		11	2	3	6	0	0	M
			18%	27%	**55%**	0%	0%	

Table 5-8: Susceptibility, Instability and Vulnerability Rankings for Compartments and Cells Compartment ranks were allocated from the mean ranking of the component cells. Rankings from the Gascoyne study (Eliot *et al.* 2012b) were used for compartments north of Murchison River mouth.

Note the component cells are of unequal coastal extent and assessment of the primary compartments is based on an early version of the OSRA database.

Primary Sediment Cell	Susceptibility				Instability				Vulnerability			
	Compartment Rank			Cell Rank	Compartment Rank			Cell Rank	Compartment Rank			Cell Rank
	1°	2°	3°		1°	2°	3°		1°	2°	3°	
64. Murchison River to Nunginjay S. C. N.	M	M	M	M	M	H	H	H	M	M-H	M-H	M-H
63. Red Bluff to Murchison River				H				M				M-H
62. Pot Alley to Red Bluff			H	H			H	H			H	H
61. Bluff Point to Pot Alley				H				H				H
60. Wagoe Well to Bluff Point				M				H				M-H
59. Wagoe Well South to Wagoe Well	M	M		M	H	H		H	M-H	M-H		M-H
58. Yanganooka to Wagoe Well South			M	M			H	H			M-H	M-H
57. Sandlewood Bay to Yanganooka				H				H				H
56. Shoal Point to Sandlewood Bay				M				H				M-H
55. Eagles Nest to Shoal Point			M	M			H	H			M-H	M-H
54. Broken Anchor Bay to Eagles Nest				M				H				M-H
53. Menai Cliffs to Broken Anchor Bay				M				H				M-H
52. White Cliffs to Menai Cliffs		M	M	M		H	H	H		M-H	M-H	M-H
51. Whale Boat Cove to White Cliffs				M				H				M-H
50. Bowes River to Whale Boat Cove	M		L	L	H		H	H	M		M	M
49. Coronation Beach to Bowes River			M	M			M	M			M	M
48. Buller to Coronation Beach		M	M	M		M	M	M		M	M	M
47. Glenfield to Buller				M				M				M
46. Chapman to Glenfield				M				H				M-H
45. Saint Georges to Chapman				M				L				L-M
44. Marina to Saint Georges				H				H				H
43. Geraldton East to Marina												
42. Geraldton West to Geraldton East			M	No data			M	No data			M	No data
41. Connell Road to Geraldton West												
40. Pages to Connell Road		M		M		H		L		M		L-M
39. West End to Pages				M				M				M
38. Point Moore to West End				M				M				M
37. Separation Point to Point Moore				M				H				M-H
36. Cape Burney North to Separation Point			M	M			H	M			M-H	M
35. Greenough North to Cape Burney North				M				M				M
34. Cape Burney South to Greenough North				M				H				M-H
33. West Bank to Cape Burney South			M	M			H	H			M-H	M-H
32. Phillips Road Coast to West Bank				M				H				M-H
31. Lucys to Phillips Road Coast				M				H				M-H
30. Duncans Pool to Lucys			M	M			H	H			M-H	M-H
29. Flat Rocks to Duncans Pool		M		M		H		M		M-H		M
28. Headbutts to Flat Rocks				L				M				L-M
27. Shire Boundary to Headbutts				L				H				M
26. Bookara South to Shire Boundary			L	L			H	H			M	M
25. Nine Mile Beach to Bookara South				M				H				M-H
24. Seven Mile Beach to Nine Mile Beach	M			L	M			M	M			L-M
23. Harleys Hole to Seven Mile Beach		L	L	L		M	M	M		L-M	L-M	L-M
22. Dongara North to Harleys Hole				L				M				L-M
21. Leander Point to Dongara North				L				M				L-M
20. South Leander Point to Leander Point			M	M			H	H			M-H	M-H
19. White Point to South Leander Point		M		M		H		H		M-H		M-H
18. Cliff Head to White Point			M	M			H	H			M-H	M-H
17. North Knobby Head to Cliff Head		L	L	L		L	L	L		L	L	L
16. South Illawong to North Knobby Head				L				L				L
15. Gum Tree Bay to South Illawong			L	L			M	M			L-M	L-M
14. Coolimba to Gum Tree Bay				L				M				L-M
13. Tailor Bay to Coolimba				L				M				L-M
12. Leeman to Tailor Bay				L				M				L-M
11. Webb Islet to Leeman		L		L		M		L		L-M		L
10. Unsurveyed Point to Webb Islet			M	M			M	L			L-M	L-M
9. Little Anchorage to Unsurveyed Point				M				M				M
8. Point Louise to Little Anchorage				M				M				M
7. Green Head to Point Louise				M				M				M
6. South Bay to Green Head				M				M				M
5. Fisherman Islands to South Bay			M	L			M	M			L-M	L-M
4. South Fisherman to Fisherman Islands		M		L		M		L		M		L
3. Sandy Cape to South Fisherman				M				L				L-M
2. Sandland to Sandy Cape			M	M			M	M			M	M
1. North Head to Sandland				M				M				M

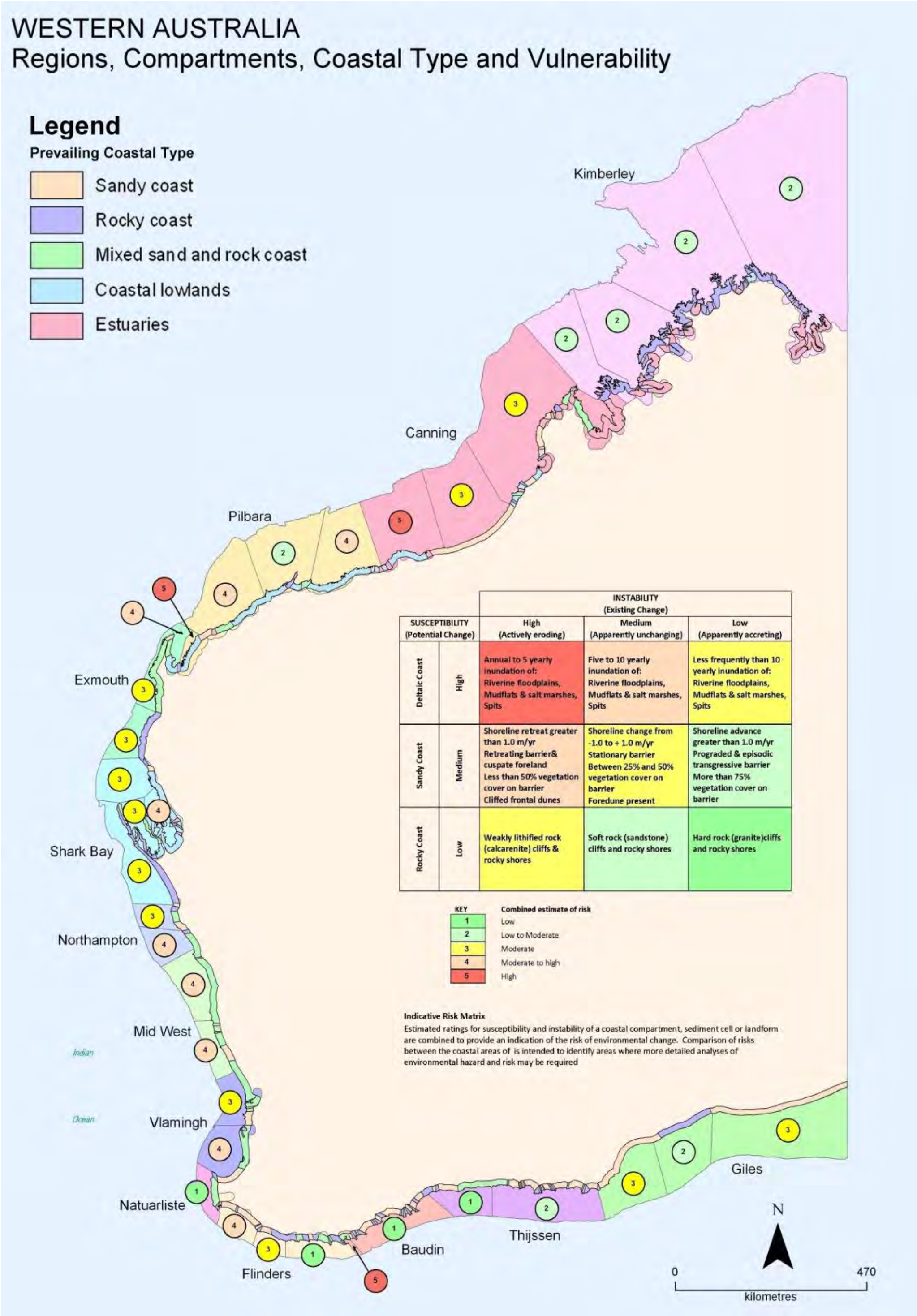


Figure 5-3: Coastal Landform Types and Vulnerability for Western Australia

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

The risk matrix considered very large scale land systems, particularly sandy, rocky and deltaic coastal systems relevant for a State-wide assessment of coastal vulnerability. This is the same approach as that used for consideration of the more detailed land systems of the Mid-West coast shown in Figure 2-10. (Source: Eliot et al. 2011a).

6. Areas of Planning Interest

Areas of Planning Interest are those that are under development pressure or have been identified for future land use change. In some cases, these areas have been identified in Local Planning Strategies, sub-regional plans or local strategic plans (WAPC 1996; DPI 2005; Shire of Irwin 2007; Shire of Northampton 2008; Department of Planning: DoP 2010a, b, c, d, e). Further information on relevant planning documents at regional and local scales is contained in a summary document prepared by the Department of Planning (DoP 2010f). Prior advice for each of these Areas of Planning Interest has been addressed in past local strategies and the *Batavia Coast Strategy* (Landvision & UWA 2001).

The Areas of Planning Interest identified for the Coorow to Northampton shires include from south to north (Figure 1-1):

- Green Head
- Leeman
- Dongara/Port Denison
- Geraldton
  - Cape Burney North to Separation Point
  - Point Moore Tombolo
  - Chapman River to Glenfield
  - Glenfield to Buller
- Horrocks
- Port Gregory
- Kalbarri

Each Area of Planning Interest includes: identification of the relevant sediment cells; identification of the levels of susceptibility, instability and vulnerability across those cells; a comparison of historic aerial imagery; and initial planning advice.

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

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

6.1. GREEN HEAD

The Green Head townsite is zoned to expand slightly to the south east (to Ocean View Drive) along the coast with some infill of Tourism developments (O'Brien Planning Consultants 2010). The Area of Planning Interest is located partly within Cell 6 (South Bay to Green Head) and Cell 7 (Green Head to Point Louise) (Figure 6-1; Figure C - 53; Cell descriptions are in

Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10). Green Head is an area where two sets of constraints may be appropriately considered in the planning process.

Coastal susceptibility, instability and vulnerability: Both cells have moderate susceptibility and moderate instability. Hence, the area has a moderate vulnerability with coastal risk of foredune destabilisation and scarping, beach rotation, dune mobility and blowouts possibly presenting a moderate constraint to development. The most vulnerable areas are the beaches and foredunes in closest proximity to the headlands. These are considered to be manageable constraints.

Advice: Construction on the foredune and frontal dunes is likely to be affected by the vulnerability of the coast to metocean processes, most significantly adjacent to the headlands. It is advisable to align beach access away from the prevailing wind direction to minimise the risk of blowouts and initiation of sandsheets.

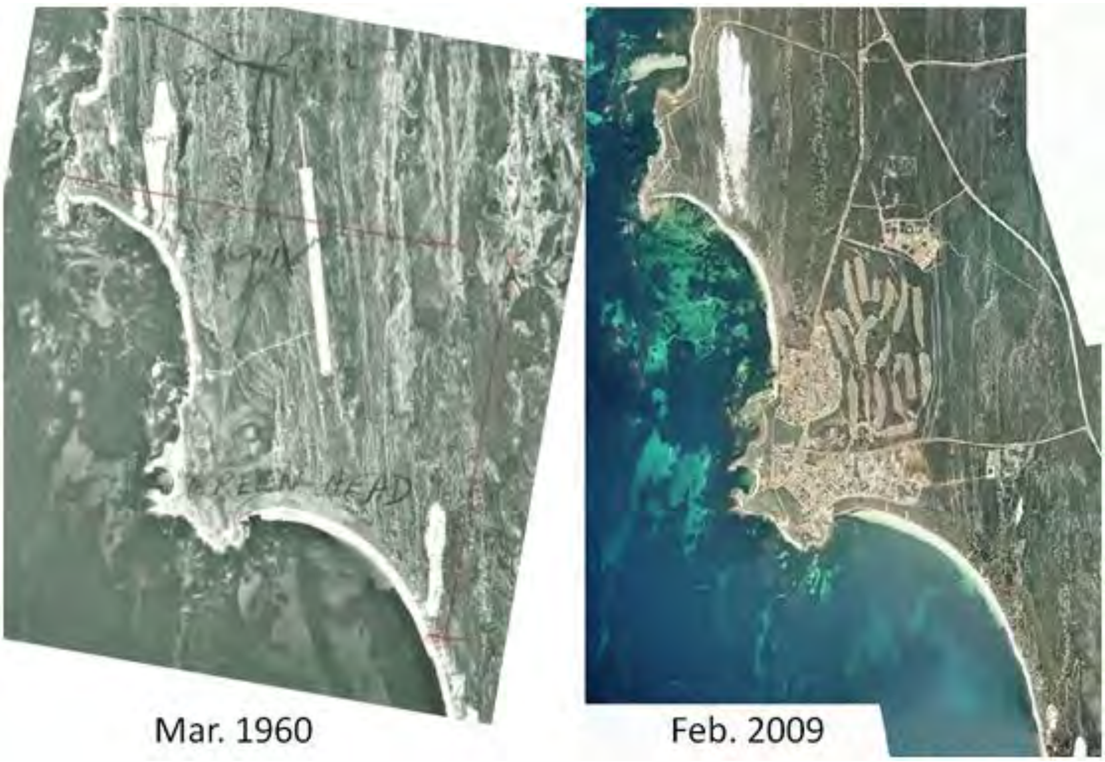


Figure 6-1 : Aerial Photography Green Head (1960 and 2009)

Further studies: It is recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009; eg. Rollason & Haines 2011) be conducted for landforms abutting the coast of Cells 6 and 7, spanning Green Head, given that the coast displays evidence of long-term retreat (Gozzard 2010) and there is a considerable area lowland immediately landwards of the Holocene dunes**.** The information could then be used to develop future adaptation and coastal management plans. The following studies may be used to inform the hazard and risk assessment:

1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique);

2. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and the incidence of extreme storm events;
3. Detailed consideration of water levels in relation to impacts on the foredune landforms and inundation levels on the lowlands to landwards;
4. Determination of the areas in the vicinity of Green Head susceptible to inundation under the projected rise in sea level and extreme events over a planning horizon of 100 years.
5. Determination of a sediment budget based on the identification of sediment sources, sinks and key transport pathways with a focus on the role of mobile dunes; and
6. Consideration of beach response to storm events and the longer-term non-linear response of perched beach and dune features to changes in sea level. This should be considered in the context of the underlying rock structure. Projected long-term changes should be considered for foredunes and sediment deposits in small embayments.

6.2. LEEMAN

The Leeman townsite is zoned to expand south and east of Indian Ocean Drive (O'Brien Planning Consultants 2010). The Area of Planning Interest is located partly within Cell 11 (Webb Islet to Leeman) and Cell 12 (Leeman to Tailor Bay) with Ti-tree Point separating the two cells (Figure 6-2; Figure C - 51; Cell descriptions are in Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10).

Coastal susceptibility, instability and vulnerability: Both cells have low susceptibility with low instability for the southern cell (Cell 11) and moderate instability for the northern cell (Cell 12). There is a low vulnerability south of Ti-tree Point with coastal risk of dune mobility unlikely to be a constraint to development. A low-to-moderate vulnerability exists north of Ti-tree Point with coastal risk of frontal dune mobility, further foredune retreat and destabilisation of dunes possibly presenting a low constraint to development.

Advice: The low vulnerability is unlikely to present a constraint to development south of Ti-tree Point. Advisedly, any future developments to the south should maintain the existing coastal setback. Immediately north of Ti-tree Point, development closer to the coast than the present infrastructure due to potential beach retreat requires management considerations, although, the underlying rock structure reduces the susceptibility. It is advisable to align access away from the prevailing wind direction across the Leeman Townsite to minimise the risk of blowouts.

Further studies: It is recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009; eg. Rollason & Haines 2011) be conducted for landforms abutting the coast of Cells 11 and 12, spanning Leeman. The information could then be used to develop future adaptation and coastal management plans, particularly along the coast north of Ti Tree Point. The following studies may be used to inform the hazard and risk assessment:

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

3. Detailed consideration of water levels in relation to impacts on the foredune landforms and inundation levels on the lowlands to landwards with changing groundwater conditions;
4. Determination of a sediment budget based on the identification of sediment sources, sinks and key transport pathways with a focus on the role of sediment loss into perched dunes; and
5. Consideration of beach response to storm events and the longer-term non-linear response of perched beach and dune features to changes in sea level. This should be considered in the context of the geotechnical investigations. Projected long-term changes should be considered for foredunes and sediment deposits in the shallow embayments north of Ti Tree Point.

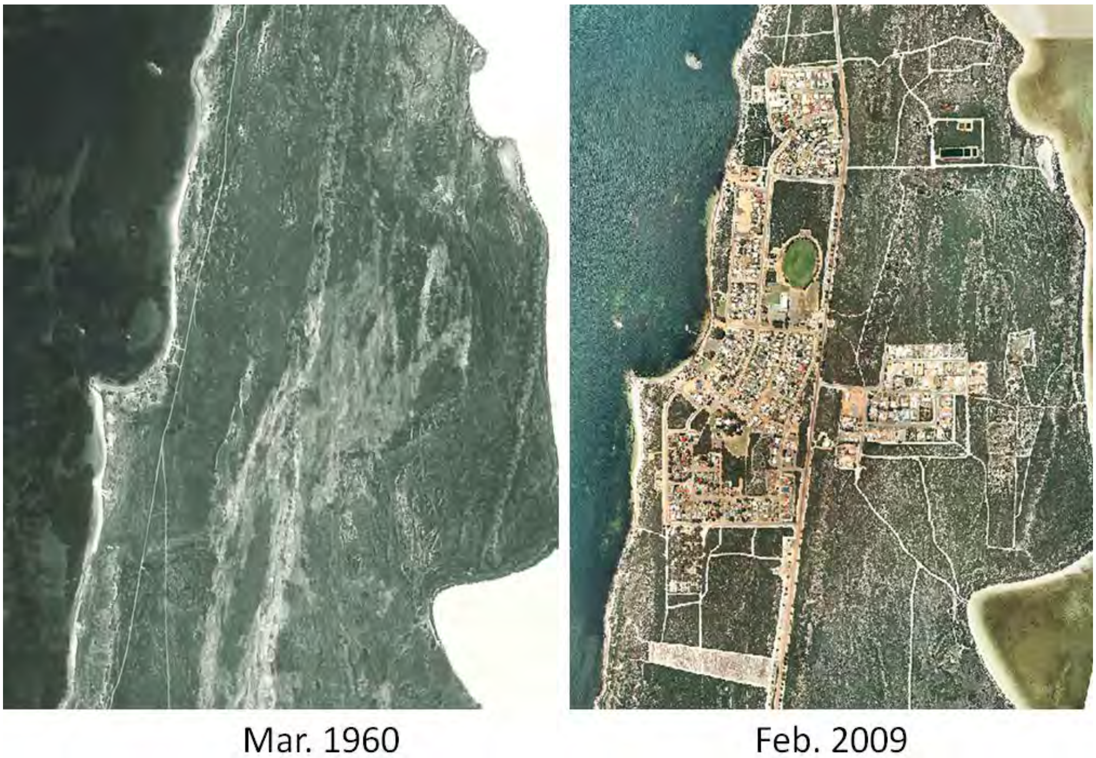


Figure 6-2 : Aerial Photography Leeman (1960 and 2009)

6.3. DONGARA/PORT DENISON

The twin Dongara and Point Denison town sites are located on both sides of the Irwin River and are incorporated as a single unit (Dongara/Port Denison Urban Area) in the Local Planning Strategy (Shire of Irwin 2007) and Town Planning Scheme (DoP 2010a). Residential development is presently expanding in the Southern Coastal Corridor of Port Denison, which could result in the relocation of the Dongara Air Field (Shire of Irwin 2007); to the north adjacent to the coast; and as infill inland in proximity to the Irwin River. The Area of Planning Interest is largely located within Cell 21 (Leander Point to Dongara North), with consideration required of Cell 20 to the south (Figure 6-3; Figure C - 37; Figure C - 38; Cell description in Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10).

Coastal susceptibility, instability and vulnerability: Cell 21 has low susceptibility and moderate instability. There is a low-to-moderate vulnerability with coastal risk of fluctuations in beach width, foredune scarping or loss, salient migration, modification in sand supply and frontal dune mobility possibly presenting a low constraint to development.

Part of the cell south of, and including, Seaspray Beach is considered to have a high vulnerability due to the influence of the Irwin River and modifications as a result of the Harbour (constructed in 1979). This section of coast has a history of recurrent erosion that is anticipated to be exacerbated and continue in future. North of this location there is moderate vulnerability for the frontal dunes and frontal barrier, with risk dropping to low for the back barrier.

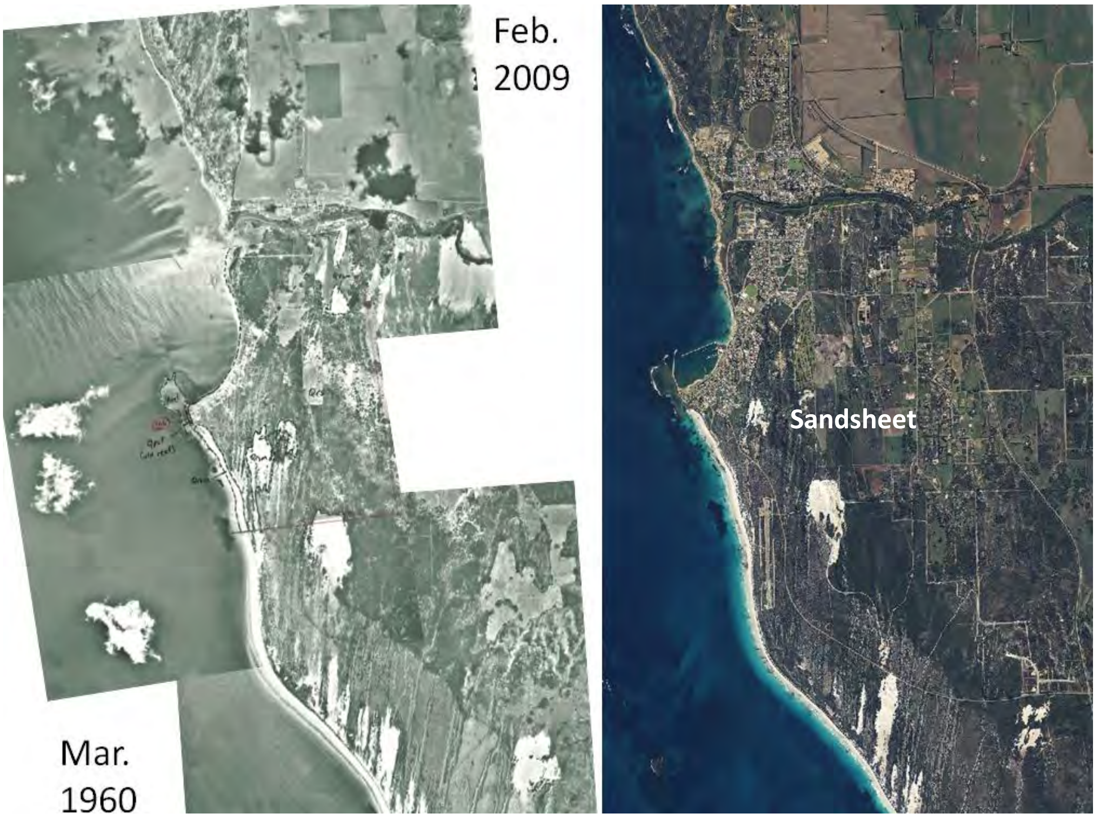


Figure 6-3 : Aerial Photography Dongara/Port Denison (1960 and 2009)

The low-lying land adjoining the Irwin River is vulnerable to inundation of the alluvial flats, approximately 1.5-4 km upstream of the mouth (Figure C - 37). Dunes and beaches adjacent to the Irwin River mouth are vulnerable to fluctuations in the barred mouth. Opening and closure of the river mouth with intermittent flooding results in the river mouth operating as a sediment source or sink (Sections 3.3.3 and 4.2.5.1). Development on the alluvial flats adjacent to the Irwin requires consideration of potential flood inundation and mitigation.

The expansion of the Southern Coastal Corridor at Port Denison is vulnerable to activation and migration of blowouts and sandsheets. The Town Planning Scheme (DoP 2010a) suggested a 500 m buffer from the toe of the dune for a sandsheet that has migrated 252m NNE in 49 years (labelled on Figure 6-3). This definition of setback from the dune toe is likely to be insufficient for this sandsheet.

Advice: The definition of setback of 500m from the dune toe is likely to be insufficient for management of the sandsheet in the Southern Coastal Corridor at Port Denison and revision of this setback is advised. In addition, if the airport was moved to the corner of Brand Highway and Kailis Drive (Shire of Irwin 2007) consideration of vulnerability to blowouts, sandsheet migration and coastal access alignment should be included in the planning process.

Blowouts and sandsheet activation are of concern, particularly south of the harbour. It is advised that coastal access be designed to minimise loss of vegetation of the foredunes and frontal dunes. Beach access ways should be minimised and tracks along the coast kept well to the landward margin of the narrow foredune plain, if not abandoned altogether. The local planning strategy (Shire of Irwin 2007) recommends ORV regulation to be enforced.

Construction on the foredune, frontal dune and second dune near the Irwin River mouth and north of Port Denison Harbour is likely to be at risk coastal erosion. These landforms are vulnerable due to fluctuations in the barred river mouth operating as a sediment source or sink. The risk warrants assessment in any coastal planning process.

Coastal setback is required north of Seaspray Beach where there is potential for migration of the shoreline salient. In this context it is advised to minimise construction on the frontal dunes, and manage access on the foredunes and frontal dunes of this area.

Further studies: It is recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009; eg. Rollason & Haines 2011) be conducted for landforms abutting the coast of Cells 20 and 21, spanning the Port Denison and mouth of the Irwin River, given parts of the coast displays evidence of severe erosion**.** The information could then be used to develop future adaptation and coastal management plans. The following studies may be used to inform the hazard and risk assessment:

1. Determination of the sediment budget for the Port Denison Embayment, including examination of the roles of the Irwin River as a sediment source and sink (Section 3.3.3).
2. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) to determine the bedrock topography along the coast and the extent to which it provides natural stabilisation of the shore where development is proposed within 100m of the shore;
3. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and the incidence of extreme storm events including those associated with marine inundation and river flooding;
4. Detailed consideration of water levels in relation to impacts on the river mouth bar, foredune landforms and inundation levels on the lowlands along the estuarine reaches of the Irwin River; and
5. Consideration of beach response to storm events and the longer-term non-linear response of perched beach and dune features to changes in sea level along the coast north of the river mouth. This should be considered in the context of the underlying rock structure and the geotechnical investigations.

6.4. GERALDTON

The Geraldton area has been subdivided into four Areas of Planning Interest corresponding to the Sediment Cells of: Cape Burney North to Separation Point (Section 6.4.1), Point Moore

Tombolo (Section 6.4.2) Chapman River to Glenfield (Section 6.4.3) and Glenfield to Buller (Section 6.4.4).

6.4.1. Cape Burney North to Separation Point

This stretch of coast contains the largely developed coast along Tarcoola Beach between Cape Burney North and Separation Point in Cell 36, as well as the Greenough Townsite and Southgate Dunes (Figure 6-4; Figure C - 29; Cell descriptions are in Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10).

Coastal susceptibility, instability and vulnerability: The cell has moderate susceptibility and moderate instability. There is a moderate vulnerability with coastal risk of modifications of sediment supply from the seagrass beds, beach width fluctuations, foredune activity, dune mobility, reactivation of dune blowouts and sandsheet migration. There is also potential for migration of the salient and tombolo features at the southern and northern extents of the cell. Any of the factors listed are likely to present a significant constraint to development.

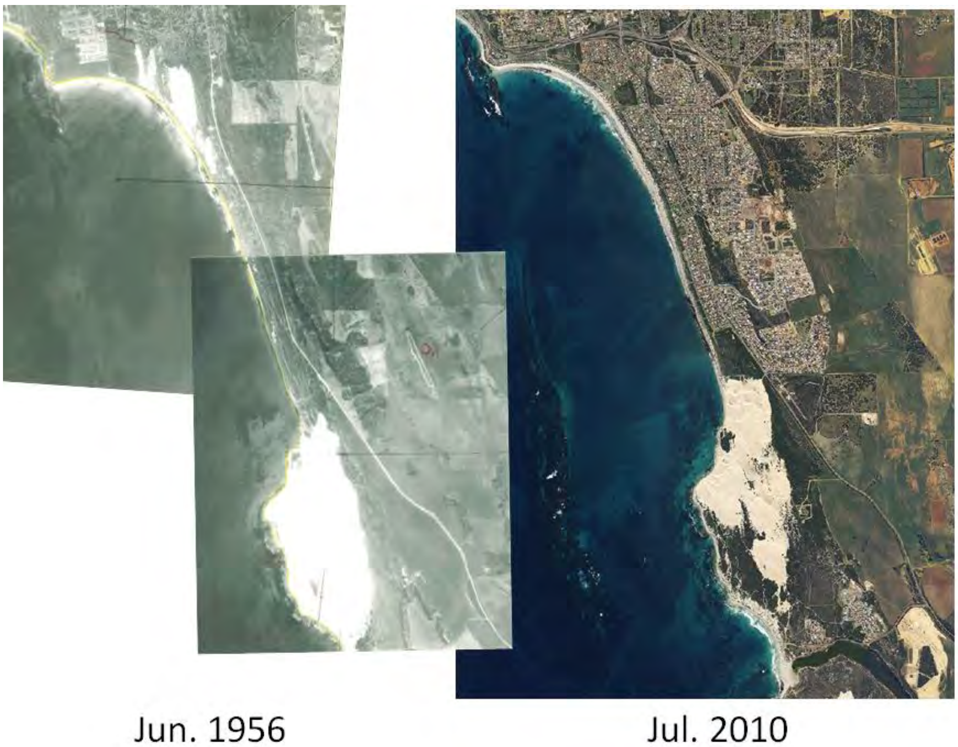


Figure 6-4 : Aerial Photography Geraldton: Cape Burney North to Separation Point (1956 and 2010)

Advice: This cell is largely developed and further construction seaward of present development requires significant management measures. Development of an area of the Southgate foredunes is anticipated. However, it is advised that this not occur without completion of the sediment budget currently being undertaken by the Department of Transport and Curtin University personnel. Southgate Dune provides a supply of sediment to Tarcoola Beach (Tecchiato & Collins 2011). Modification to the sandsheet will potentially result in enhanced retreat of Tarcoola Beach, including the foredune and primary dunes of this cell. Although stable at present, Southgate Dunes are approaching the Brand Highway and will require ongoing sand management.

Further studies: It is recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009; eg. Rollason & Haines 2011) be conducted for landforms abutting the coast in Cells 36 to 39 inclusively, spanning the area from Cape Burney South to Pages Beach inclusively. Acquisition of LiDAR imagery and its interpretation for the marine waters between Cape Burney South and Glenfield Beach, including Cells 36 to 46 should be viewed as an important contribution to the risk assessment process. Parts of the coast display evidence of severe erosion while, at times others have been severely impacted by extreme events. Additionally, there are unknowns concerning the degree of connectivity between and within sediment cells. Hence, an important issue to address is the extent to which current problems are likely to impact on other parts of the coastal cells in which they occur. Information gathered in a full risk assessment could be used to develop future adaptation and coastal management plans to mitigate expansion of the problems. The following studies may be used to inform the hazard and risk assessment:

1. Extension of sediment budget work completed for the Tarcoola Embayment to include determination of the sediment budget for the African Reef Embayment at the mouth of the Greenough River. This should include examination of the roles of the Greenough River as a sediment source and sink (Section 3.3.3).; the development of the foredune ridge along the southern margin of Southgate Dune; and sediment bypassing around Cape Burney North;
2. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and the incidence of extreme storm events including those associated with marine inundation and river flooding;
3. Detailed consideration of water levels in relation to opening and closing of the river mouth bar, erosion of foredunes and inundation of the lowlands along the estuarine reaches of the Greenough River;
4. Monitoring of shoreline movement and foredune changes along the coast around Cape Burney North as well as along Tarcoola Beach through monthly measurement of beach and foredune profiles;
5. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) to determine the bedrock topography along the coast within 100m of the shore and the extent to which it provides natural stabilisation of the coastal landforms;
6. Consideration of beach response to storm events and the longer-term non-linear response of perched beach and dune features to changes in sea level along the coast south of the mouth of Greenough River. This should be considered in the context of the underlying rock structure and the geotechnical investigations.

6.4.2. Point Moore Tombolo

This stretch of coast contains land zoned for community purposes landward of Willcock Road, with residential zoning and light industrial zoning inland of Willcock Road (DoP 2010c). The Area of Planning Interest encompasses Cell 37 (Separation Point to Point Moore) and Cell 38 (Point Moore to West End), located on the southern side of the Point Moore Tombolo (Figure 6-5; Figure C - 29; Cell descriptions are in Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10).

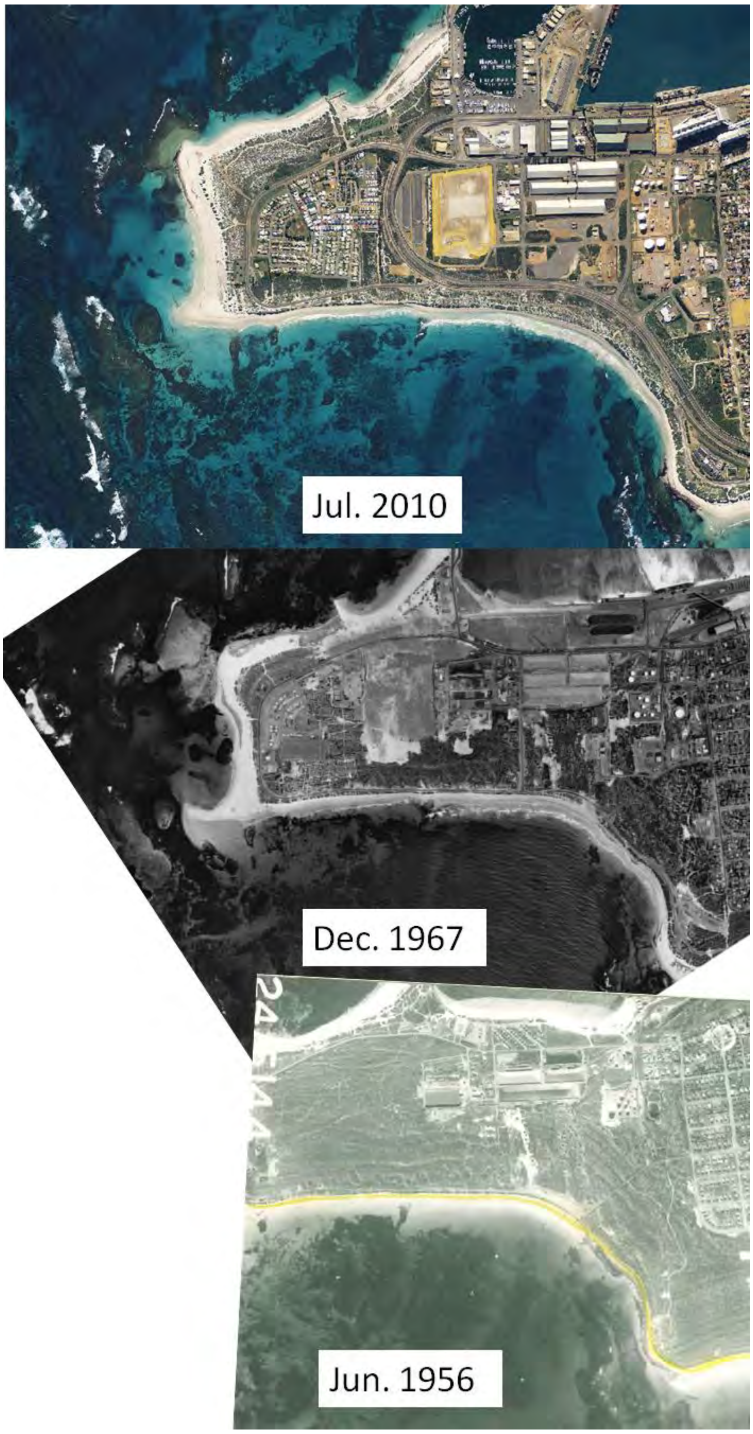


Figure 6-5 : Aerial Photography Geraldton: Point Moore Tombolo (1956, 1967 and 2010)

Coastal susceptibility, instability and vulnerability: Both cells include shoreline salients and have moderate susceptibility. The southern cell (Cell 37) has high instability and the northern cell (Cell 38) moderate instability. The southern cell (Cell 37) has a moderate-to-high vulnerability with coastal risk of storm surge inundation (PWD 1983b), salient/tombolo migration and fluctuations, sand spit and beach width fluctuations, mobility of foredune plains, foredune and primary dune activity/scarping and modifications to the rate of sediment supply from seagrass beds likely to be a significant constraint to development. The same coastal risks may be a moderate constraint to development in the northern cell (Cell 38).

Advice: Further construction seaward of the present residential buildings on the Point Moore Tombolo requires consideration of potential landform migration and shoreline retreat. There is an historical record of shoreline retreat towards Willcock Road, with investigations advising potential reconstruction of the road further landward. Revision of the advised setback is required for this tombolo, with the beach and foredune plains vulnerable or, alternatively, some consideration should be given to the nature and cost of future coastal stabilisation works. An adaptation plan could also be developed for this site with regard to potential changes in metocean forcing, particularly changes in sea level.

Further studies: It is recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009; eg. Rollason & Haines 2011) be conducted for landforms abutting the coast in Cells 36 to 39 inclusively, spanning the area from Cape Burney South to Pages Beach inclusively. Acquisition of LiDAR imagery and its interpretation for the marine waters between Cape Burney South and Glenfield Beach, including Cells 36 to 46 should be viewed as an important contribution to the risk assessment process. Parts of the coast display evidence of severe erosion while, at times others have been severely impacted by extreme events. Additionally, there are unknowns concerning the degree of connectivity between and within sediment cells**.** Hence, an important issue to address is the extent to which current problems are likely to impact on other parts of the coastal cells in which they occur. Information gathered in a full risk assessment could be used to develop future adaptation and coastal management plans to mitigate expansion of the problems. The following studies may be used to inform the hazard and risk assessment:

1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) to determine the bedrock topography along the coast and the extent to which it potentially provides natural stabilisation of the coastal landforms;
2. Identification of beach response to storm events and the longer-term non-linear response of perched beach and dune features to short and long-term changes in sea level along the coast;
3. Development and implementation of a nested beach profile survey program monitoring and analyses of closely spaced (100m) shoreface profiles including: (a) quarterly surveys of the shoreface; (b) monthly surveys of the nearshore and foredune profiles around Point Moore between Separation Point and Pages Beach; and (c) daily surveys of the beachface between Separation Point and Point Moore for 36 days during the break in season during change to sea breeze dominated conditions;
4. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and the incidence of extreme storm events;
5. Numerical modelling of sediment transport as part of coastal sediment budget estimation for the Tarcoola and Champion Bay embayments with verification based on (a) results of the geological investigations of the sediment budget; (b) trend surface analyses of the distribution of sediment characteristics in the two embayments; and (c) an assessment of historical and current shoreline changes, the latter to include results from a monitoring program; and

6. Development of strategies to minimise or mitigate erosion problems along the coast between Separation Point and Point Moore based on the information above and without deleterious downstream effects.

6.4.3. Chapman River to Glenfield

This stretch of coast contains the Drummond Cove development, which is zoned residential for a 2.5km distance along the coast encompassing the Glenfield salient/tombolo (Figure 6-7; Figure 6-8; DoP 2010b). The Area of Planning Interest is Cell 46, located between the Chapman River mouth and the Glenfield salient (Figure 6-6; Figure C - 27; Cell descriptions are in Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10).

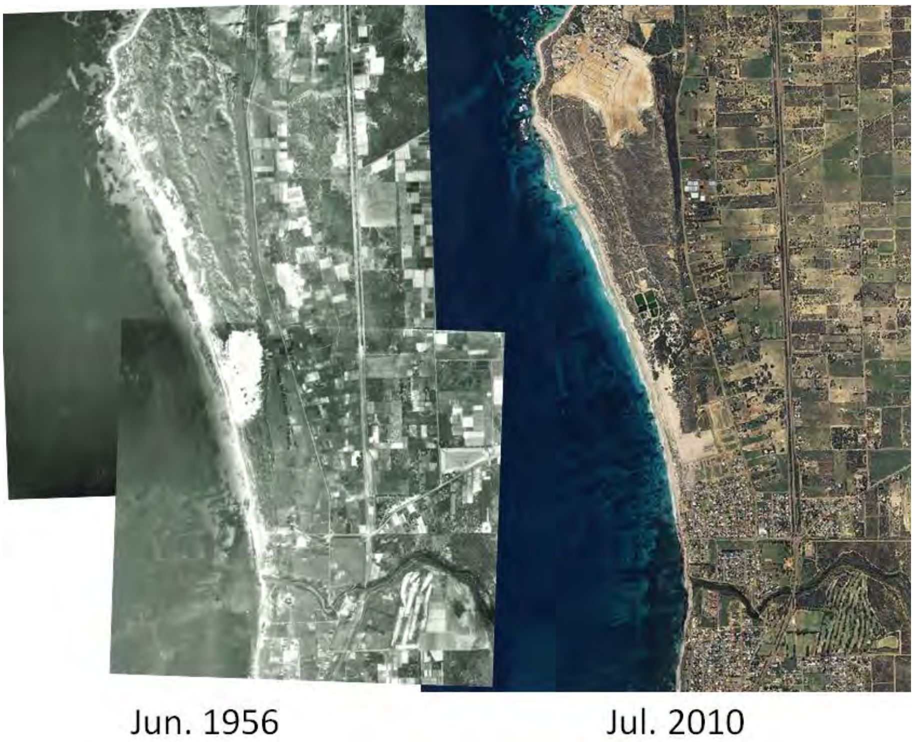


Figure 6-6 : Aerial Photography Geraldton: Chapman River to Glenfield (1960 and 2009)

Coastal susceptibility, instability and vulnerability: The cell has moderate susceptibility and high instability. There is a moderate-to-high vulnerability with coastal risk of storm surge inundation (PWD 1983b), Chapman River activity and fluctuation of the bar as a source or sink of sediment; foredune activity; dune mobility; foredune plain retreat; reactivation of dune blowouts; sandsheet migration; and migration of the Glenfield salient likely to present a significant constraint to development. This site is vulnerable to changes in metocean forcing within Champion Bay. The sediment budget of the embayment is currently subject to investigation by the Department of Transport and Curtin University personnel (Tecchiato & Collins 2011).

Advice: Construction on the foredune, blowouts and foredune plains of this cell will require significant management measures. An allowance for potential reactivation of sandsheets and formation of blowouts should be considered in any development, particularly with present construction occurring on revegetated blowouts. It is advised to consider the potential landform migration or retreat adjacent to the Chapman River mouth and at the Glenfield salient.

Alignment of beach access away from the prevailing wind direction and restricting the number of locations to a minimum is advised to minimise the risk of blowouts.

Due to the low lying nature of the alluvial flats of the Chapman River, it is advisable to investigate the current and projected patterns of flooding and marine incursion up to 1.5km upstream of the mouth.

Further studies: It is recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009) be conducted for landforms abutting the coast in Cells 44-46 spanning the area from the marina to the rocks at Glenfield. Acquisition of LiDAR imagery and its interpretation for the marine waters between Cape Burney South and Glenfield Beach, including Cells 36 to 46 should be viewed as an important contribution to the risk assessment process. Parts of the coast display evidence of severe erosion while, at times others have been severely impacted by extreme events. Additionally, there are unknowns concerning the degree of connectivity between and within sediment cells**.** Hence, an important issue to address is the extent to which current problems are likely to impact on other parts of the coastal cells in which they occur. Information gathered in a full risk assessment could be used to develop future adaptation and coastal management plans to mitigate expansion of the problems. The following studies may be used to inform the hazard and risk assessment:

1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) to determine the bedrock topography along the coast between the Marina and Glenfield (Cells 44 to 46 inclusively)and the extent to which it potentially provides natural stabilisation of the coastal landforms;
2. Identification of beach response to storm events and the longer-term non-linear response of perched beaches and dunes north and south of the Chapman River to short and long-term changes in sea level along the coast;
3. Development and implementation of a nested beach profile survey program monitoring and analyses of closely spaced (100m) shoreface profiles including: (a) quarterly surveys of the shoreface; and (b) monthly surveys of the nearshore and frontal dune profiles.
4. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and the incidence of extreme storm events;
5. Numerical modelling of sediment transport as part of coastal sediment budget estimation for the Tarcoola and Champion Bay embayments with verification based on (a) results of the geological investigations of the sediment budget; (b) trend surface analyses of the distribution of sediment characteristics in the two embayments; and (c) an assessment of historical and current shoreline changes, the latter to include results from a monitoring program; and

6. Development of strategies to minimise or mitigate erosion problems along the coast between the Marina and Glenfield Beach based on the information above and without deleterious downstream effects.

6.4.4. Glenfield to Buller

The City of Geraldton-Greenough to the south and the Shire of Chapman Valley to the north are located between Glenfield Beach and Buller River. The reach of coast contains the Drummond Cove development, which is zoned residential for a 2.5km distance along the coast and encompasses the Glenfield salient/tombolo (Figure 6-7; Figure 6-8; DoP 2010b). Plans for the area include consideration of a marina development at Drummond Cove (M.P. Rogers & Associates 2007). In the north, it contains a large active sandsheet and a salient/tombolo that is zoned for general farming (DoP 2010d). Land north of Buller River is reserved for industrial investigations related to the Oakajee Port.

The Area of Planning Interest is Cell 47, located between two headlands and containing the Buller River (Figure 6-7; Figure 6-8; Figure C - 27; Cell descriptions are in Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10).

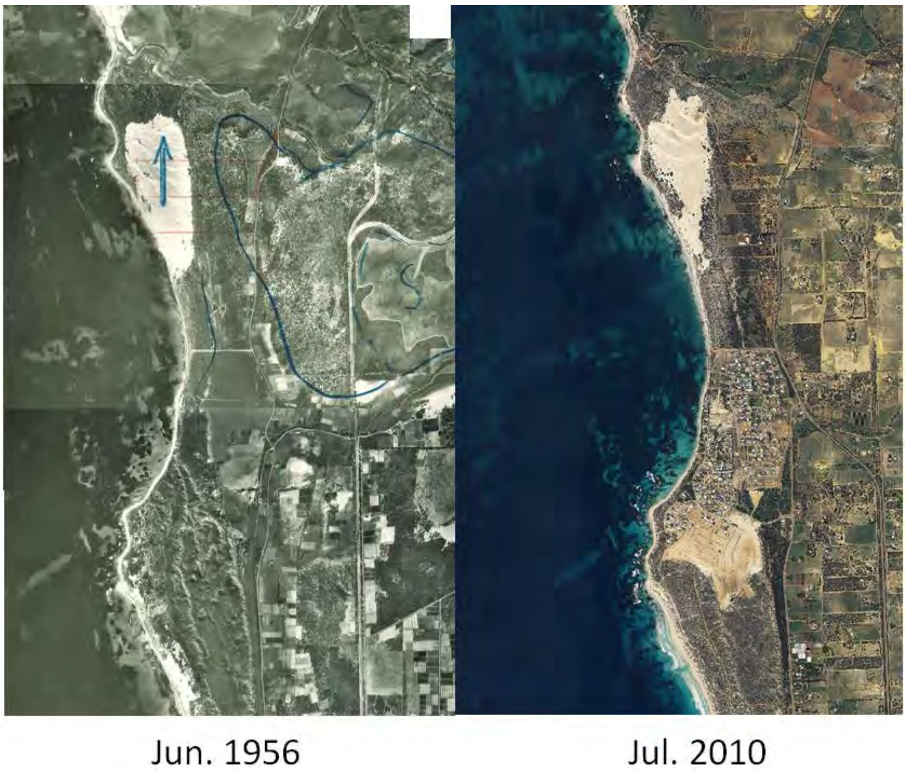


Figure 6-7 : Aerial Photography Geraldton: Glenfield to Buller (1956 and 2010)

Coastal susceptibility, instability and vulnerability: The cell has moderate susceptibility and instability. There is a moderate vulnerability with coastal risk of salient migration/retreat including retreat of foredune plains, sandsheet activation, foredune and primary dune activity, blowouts and beach width fluctuations possibly presenting a moderate constraint to development. In addition, this cell is influenced by the risk of modifications to sediment supply from seagrass beds and the nature of Chapman River mouth behaving as a source or sink of sediment. The proposed Drummond Cove development is constructed on a historically active creek. Such locations have produced on-going management problems at a number of locations around the State, including at Esperance (Jones *et al.* 2009) and Exmouth (Martens *et al.* 2000).

Figure 6-8: Aerial Photography: Glenfield (1956 and 2010)

Advice: Development closer to the coast than the present infrastructure requires consideration of potential landform migration or retreat. This is most relevant at the southern extent of the cell. It is advisable to align access away from the prevailing wind direction and restrict the number of locations to a minimum, to minimise the risk of blowouts.

Development between the toe of the present sandsheet in the northern half of the cell and the Buller River requires consideration of potential sandsheet migration.

Further studies: It is recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009) be conducted for landforms abutting the coast in Cells 47 and 48 spanning the area from the rocks at Glenfield to the Buller River. The embayment forming this part of the coast has the features of a classic sediment cell. There are unknowns concerning the degree of connectivity within the sediment cells**.** Hence, an important issue to address is the extent to which development in the southern part of the cell is likely to affect the northern sector. Information gathered in a full risk assessment could be used to develop future adaptation and coastal management plans to mitigate expansion of the problems. The following studies may be used to inform the hazard and risk assessment:

1. Determination of the main components of the sediment budget for the embayment, including identification of the likely major transport pathways between them and a gap analysis of relevant available information;
2. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) to determine the bedrock topography along the southern half of the coast within the Area of Planning Interest and the extent to which it provides natural stabilisation of the shore;

3. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and the incidence of extreme storm events including those associated with marine inundation; and
4. Consideration of beach response to storm events and the longer-term non-linear response of perched beach and dune features to changes in sea level along the coast north of the river mouth. This should be considered in the context of the underlying rock structure and the geotechnical investigations.

6.5. HORROCKS

Recent townsite expansion has occurred above the scarp to the east of the townsite at Horrocks Beach and is setback from the coast. Any future subdivision and release of land requires the preparation of a Structure Plan (DPI 2005). The Area of Planning Interest is located within Cell 50 (Bowes River to Whale Boat Cove) (Figure 6-9; Figure C - 19; Cell description in Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10).

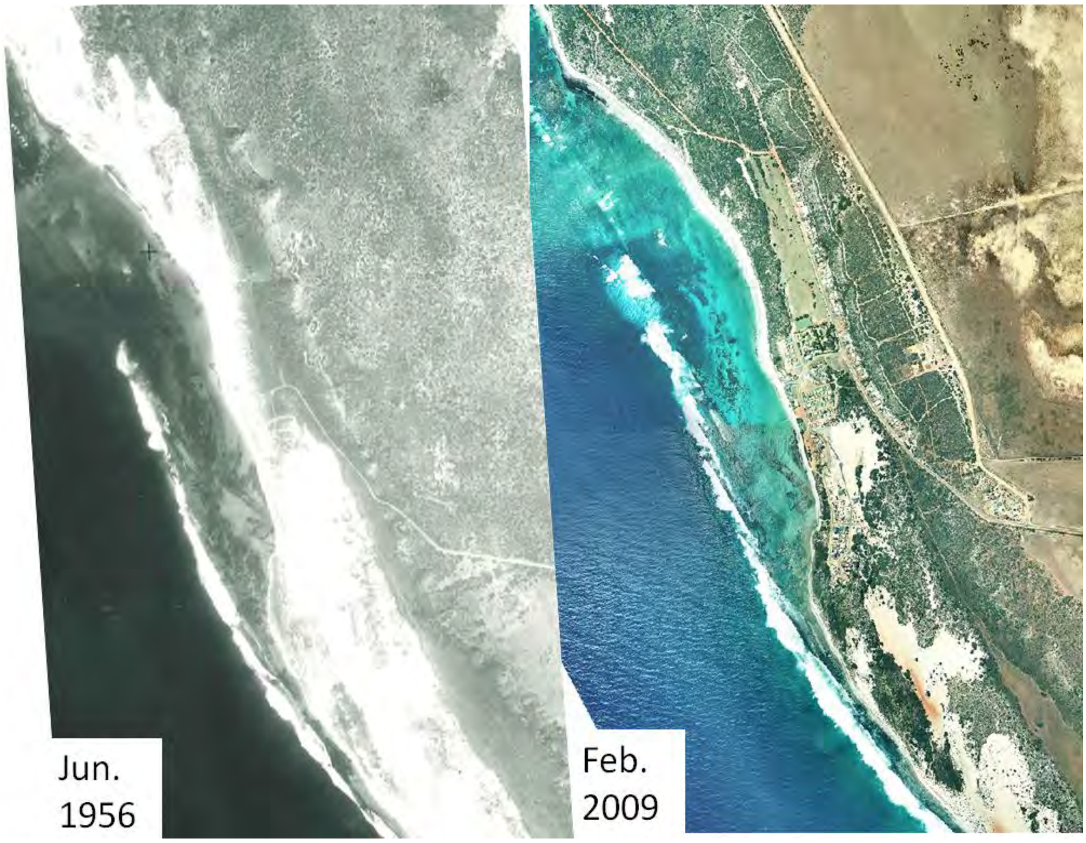


Figure 6-9 : Aerial Photography Horrocks (1956 and 2009)

Coastal susceptibility, instability and vulnerability: The cell has low susceptibility and high instability. There is a moderate vulnerability with coastal risk of salient migration, dune mobility and sandsheet migration possibly presenting a moderate constraint to development.

Advice: The least vulnerable location for expansion of the Horrocks townsite is to the east of the recent development on the scarp although some expansion onto higher ground on the inland part of the salient south of the existing townsite is feasible. However expansion of the townsite to the south is feasible but would require stabilisation of the dunes between the townsite and Bowes River. The area is vulnerable to mobile dunes and sandsheets as has occurred historically, with potential for sand transport within any development. Some of the dune blowouts are presently stabilising, but have the potential to reactivate or mobilise under changing wind forcing and sediment supply.

Development closer to the shore than the present infrastructure requires consideration of potential landform migration. It is advisable to align access away from the prevailing wind direction to minimise the risk of blowouts.

Further studies: Horrocks Beach is part of a sediment cell extending from the Bowes River to Whaleboat Cove and should be managed as such. It is recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009) be conducted for landforms abutting the coast in Cell 50. The components of the cell are known and have been described in coastal management plans. There are unknowns concerning the degree of connectivity within the sediment cells**.** Hence, an important issue to address is the extent to which development in the southern part of the cell is likely to affect the northern sector. Information gathered in a full risk assessment could be used to develop future adaptation and coastal management plans to mitigate expansion of perceived problems. The following studies may be used to inform the hazard and risk assessment:

1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) to determine the bedrock topography along the southern half of the coast within the Area of Planning Interest and the extent to which it provides natural stabilisation of the shore;
2. Determination of the main components of the sediment budget for the cell, including identification of the likely major transport pathways between the Bowes River and Whaleboat Cove;
3. Gap analysis of relevant available information concerning the sediment cell (Cell 50) and its components;
4. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and the incidence of extreme storm events including those associated with marine inundation; and
5. Consideration of beach response to storm events and the longer-term non-linear response of the perched beach and dune features to changes in sea level along the coast. This should be considered in the context of the underlying rock structure and the geotechnical investigations.

6.6. PORT GREGORY

The wider area surrounding Port Gregory is zoned rural, with any coastal development requiring a coastal management policy plan (Department for Planning & Infrastructure 2008). However, no lots are presently available for development. The Port Gregory Area of Planning Interest is located within Cell 54 (Broken Anchor Bay to Eagles Nest), with rural zoning extending north into Cell 55 (Eagles Nest to Shoal Point) (Figure 6-10; Figure C - 13; Figure C - 15; Cell description in Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10).

Coastal susceptibility, instability and vulnerability: The cell containing Port Gregory has moderate susceptibility and high instability. There is a moderate-to-high vulnerability with coastal risk of salient migration and/or retreat, dune mobility, blowouts, sandsheet re-activation and reduced sediment supply (associated with Hutt River) likely to present a significant constraint to development. The cell to the north of Port Gregory (Cell 55) also has moderate susceptibility and high instability. This cell has a moderate-to-high vulnerability with coastal risk of dune mobility, blowouts and sandsheet migration and re-activation likely to present a significant constraint to development.

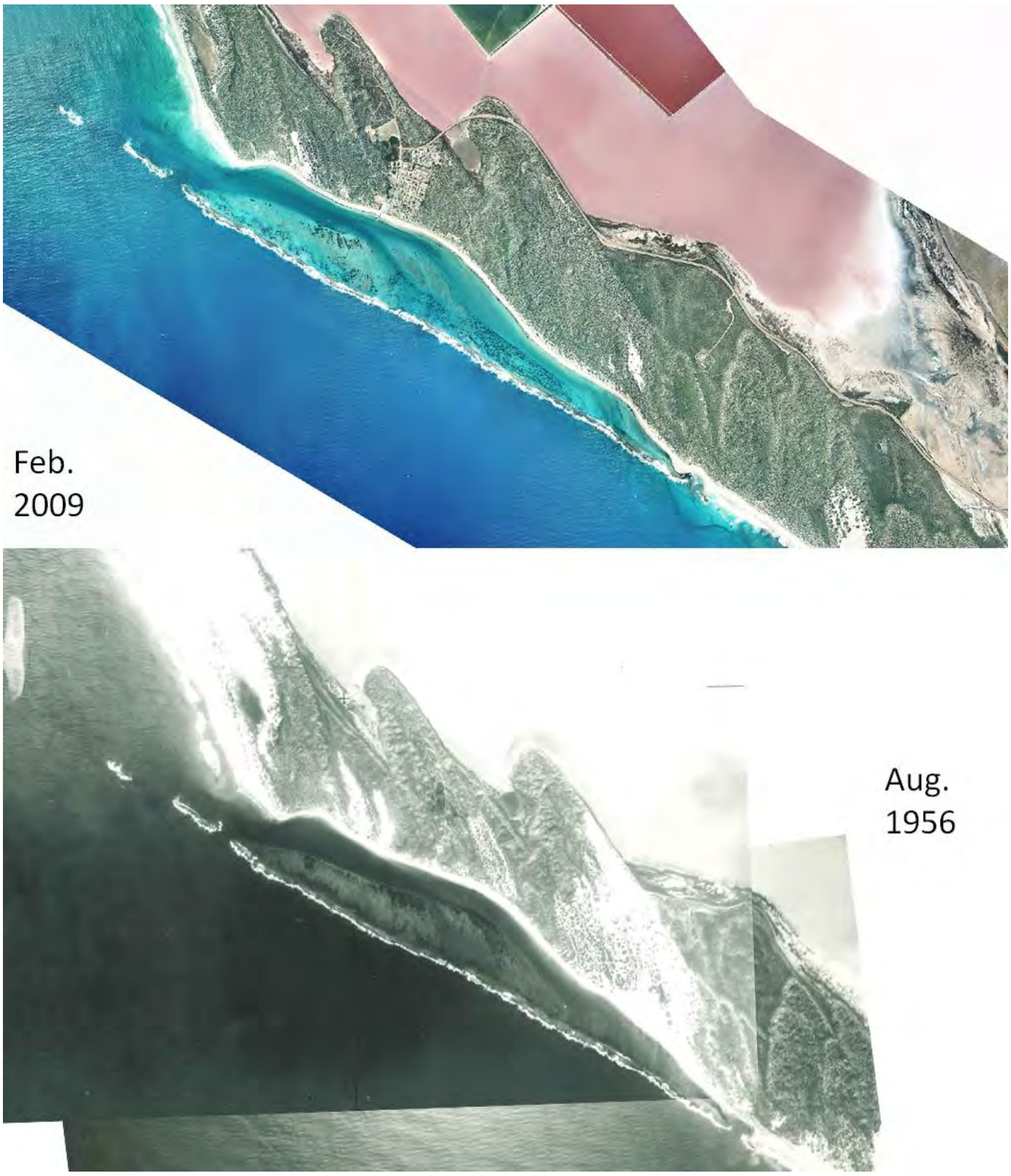


Figure 6-10 : Aerial Photography Port Gregory (1956 and 2009)

Advice: Any development north of Eagles Nest requires consideration of fluctuations in dune mobility and activity on the narrow, high barrier. The shoreline has undergone retreat historically and the majority of this coast is likely to be vulnerable to salient migration, dune blowouts and sandsheet activity, even if a significant setback is included. It is advisable to align access away from the prevailing wind direction to minimise the risk of blowouts.

Further studies: Port Gregory is part of a large sediment cell extending from Whaleboat Cove to Bluff Point (Cells 51 to 60). The two cells in the Area or Planning Interest (Cells 54 and 55) are subsets of the larger cell, and are salients tied to rock outcrops at Eagles Nest and Shoal Point. It is strongly recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009) be conducted for landforms abutting the coast in both cells. There are unknowns concerning the degree of protection afforded by bedrock topography, sources of sediment for barrier development including sediment from the Hutt River during extreme flood events, the propensity of the barrier to retreat and the phases of dune instability along the coast**.** Hence, an important issue to address is the extent to which this part of the coast is susceptible to change. Cells 54 and 55 have a moderate stability rating but the rating would be high if sediment supply to the barrier is low and the barrier is not perched on a bedrock surface. The following studies may be used to inform the hazard and risk assessment:

1. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) to determine the bedrock topography in the immediate vicinity of Port Gregory and any other part of the Area of Planning Interest for which development is proposed;
2. Determination of the main components of the sediment budget for the cell, including identification of the likely major transport pathways between Broken Anchor Bay and Sandlewood Bay;
3. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and the incidence of extreme storm events including those associated with marine inundation;
4. Consideration of beach response to storm events and the longer-term non-linear response of the perched beach and dune features to changes in sea level along the coast. This should be considered in the context of the underlying rock structure and the geotechnical investigations; and
5. Examination of water levels in relation to opening and closing of the river mouth bar, erosion of foredunes and inundation of the lowlands landward of the mouth of the Hutt River.

6.7. KALBARRI

Future development at Kalbarri is planned to occur east of Red Bluff Road from the present residential development to 6.5km south of the Murchison River. Additional residential and rural residential land is currently zoned around the townsite in close proximity to the coast. There is also a small residential and special use zoning between the Ajana-Kalbarri Road and the Murchison River. The Area of Planning Interest is located within Cell 63 (Red Bluff to Murchison River) (Figure 6-11; Figure C - 5; Cell description in Appendix D; Susceptibility, instability and vulnerability rankings are in Table 5-1, Table 5-4, Table 5-6 and Appendix E with classifications contained in Table 2-6, Table 2-10 and Figure 2-10).

Coastal susceptibility, instability and vulnerability: The cell has high susceptibility and moderate instability. There is a moderate-to-high vulnerability with coastal risk of flooding of ephemeral creeks, beach width fluctuations, cliff collapse, inundation of alluvial landforms, and fluctuations of the landforms within and adjacent to the estuary presenting a moderate constraint to development. Landforms in the estuary (including the bed), sand spit, bar and dune blowouts of the Murchison River mouth are mobilised during significant floods, with large volumes of sediment deposited seaward of the mouth. For example 200,000-400,000 m^3 of material was estimated to have been deposited following TC Emma in 2006. The landforms adjacent to the mouth are likely to fluctuate as the estuary switches between a sediment source or sink with flood discharge and tidal inundation (Sections 3.3.3 and 4.2.5.5).

Advice: The least vulnerable locations are those east of the Red Bluff Road with sufficient setback from ephemeral creeks such as Whitecarra Inlet or the Murchison River, to allow for flooding and activation of alluvial landforms. It is advised to minimise construction on any alluvial landforms including alluvial channels, valleys, terraces and flats due to instability and potential for inundation (Figure C - 5; Appendix C).

A further vulnerable landform is the foredune within the estuary, opposite the river mouth (Figure C - 5; Appendix C). An indication of the dynamic behaviour of the estuary and mouth is demonstrated in Figure 6-11, with the river discharging north of Chinaman's Rock in 1969 (Bailey 2005). The lower estuary, including the foredunes, is vulnerable to both marine and fluvial forcing. The mobility of the landforms within the mouth and estuary is advised to be considered for any intended use inside the estuary, including any feedback relationships with marine, fluvial and meteorologic forcing and proposed modifications to landforms. It is advised to consider this landform instability for the proposed development between Ajana-Kalbarri Road and the Murchison River.

Any development west of Red Bluff Road requires consideration of cliff stability, particularly in the vicinity of the gap in the reef system approximately 1 km south of the river mouth (Figure 6-11).

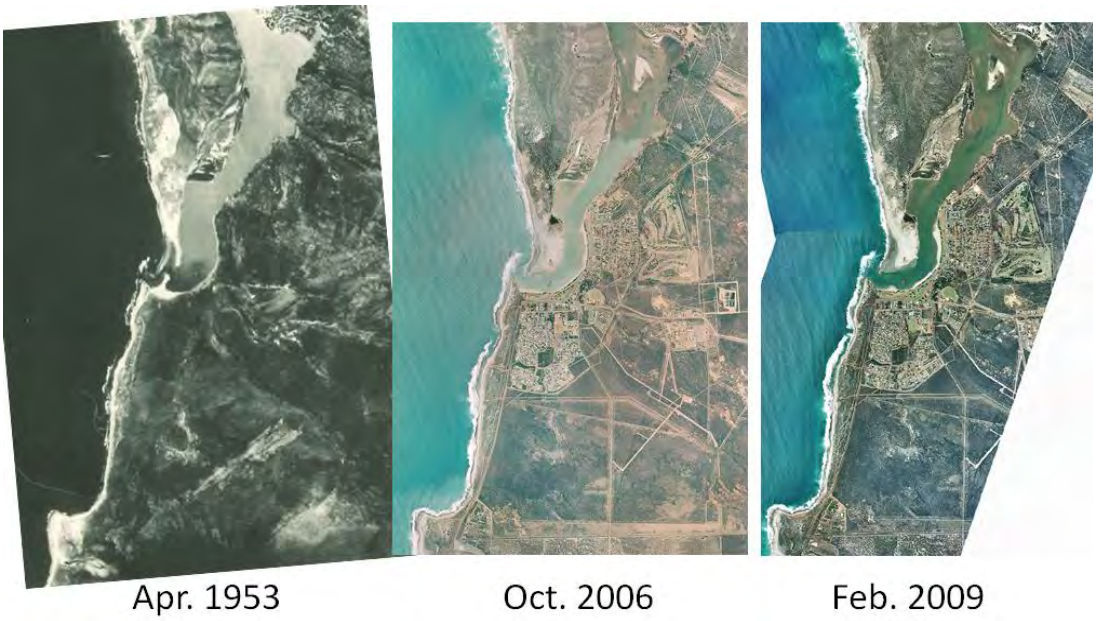


Figure 6-11 : Aerial Photography Kalbarri (1953, 2006 and 2009)

Further studies: It is recommended a coastal hazard and risk assessment following the AS/NZS ISO 31000 guidelines (Standards Australia 2009; eg. Rollason & Haines 2011) be conducted for landforms abutting the coast of in Cells 63 and 64, spanning the mouth of the Murchison River**.** The information could then be used to develop future adaptation and coastal management plans for the Area of Planning Interest and the estuarine reaches of the river. The following studies may be used to inform the hazard and risk assessment:

1. Determination of the principal components of the sediment budget for the embayment at the mouth of the Murchison River, including examination of the roles of the river as a sediment source and sink (Section 3.3.3);
2. Geotechnical investigations (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) to determine the bedrock topography along the Kalbarri shores of the estuary and the extent to which it provides natural stabilisation of the shore where development is proposed within 100m of the shore;
3. Resolution of key metocean processes, including locally generated wind waves, seasonal variability and the incidence of extreme storm events including those associated with marine inundation and river flooding;
4. Detailed consideration of water levels in relation to impacts on the river mouth bar, foredune landforms and inundation levels on lowlands along the estuarine reaches of the Murchison River; and
5. Consideration of beach responses to storm events and the longer-term non-linear response of perched beach and dune features to changes in sea level along the coast south of the river mouth. This should be considered in the context of the underlying rock structure and the geotechnical investigations.

7. Discussion & Overview

A major aim of the project was to provide strategic advice concerning the geomorphology of the Mid-West coast between North Head and the Murchison River mouth at Kalbarri, with particular reference to Areas of Planning Interest at ten sites: Green Head, Leeman, Dongara/Port Denison, Geraldton (four sites), Horrocks, Port Gregory and Kalbarri. Accordingly, coastal landforms for the Study Area have been examined at several scales: description of the coastal barrier systems and their relationship with the geologic framework provided by the underlying coastal limestone; landform patterns such as river deltas, nested parabolic dunes and blowouts, occurring in discrete sediment cells within each compartment; and the individual landforms comprising the landform patterns at each of the Areas of Planning Interest.

Two facets of coastal change were considered to provide a strategic description of the vulnerability of coastal land to current and projected changes in metocean forcing. First, the relative susceptibility or potential for erosion of a geologic structure in response to variation in metocean processes, particularly changes in sea level was estimated for different landforms comprising the sediment cells. Second, levels of relative instability were ascribed to landforms according to their current responses to metocean processes such as storms and sediment supply as well as anthropogenic factors. The estimates of susceptibility and instability were then combined to indicate the likely vulnerability of the landforms within the compartments or cells. Vulnerability in this context provides an overall estimate of landform susceptibility and instability for each sediment cell.

Combination of the susceptibility of coastal landform associations to changes in the metocean regime with the current stability of landforms they support identifies components of the coast potentially subject to risk in response to projected environmental change. Both facets are applicable at each level in the planning hierarchy and have relevance to coastal land use. Coastal plans traditionally focus on the instability of coastal landforms, with allowances for erosion (coastal setbacks) related to the historical variability of the beach-foredune system under consideration as well as projected sea level change being taken into account (WAPC 2003). However, feedback mechanisms linking structure and stability indicate landform susceptibility to metocean forcing is at least as significant, with changes in either susceptibility or stability highly likely to trigger changes to the other, particularly on unconsolidated coasts.

The potential contribution of vulnerability assessment based on the susceptibility and instability of land systems and landforms to a more complete risk assessment process, such as that proposed by ISO 31000 (Standards Australia 2009), is illustrated in Figure 7-1. This is discussed further in Section 7.4.1 below.

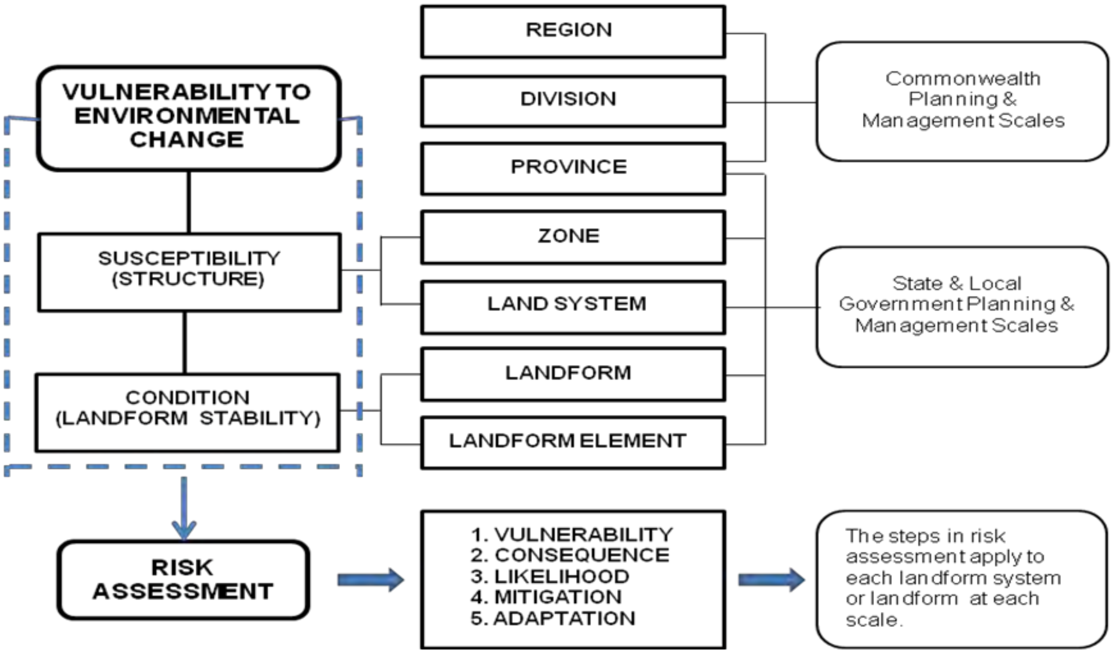


Figure 7-1: Vulnerability Assessment, Risk Assessment and Scales of Application

7.1. ASSESSMENT SCALES

At a geological timescale, the hard-rock geologic framework has provided topographic control for formation of Holocene barrier structures as unconsolidated sediment accumulated and the dune ridge evolved during the past 10,000 years, along the coast between North Head and Nuningjay Spring Coast North. Albeit slowly, barrier evolution is continuing at present as sediment is moved along and across the shore. The structure of the barrier, with unconsolidated Holocene sands overlaying the older limestone topography, implies marked geographic variation in the susceptibility of the shore to erosion and the need to apply different models for the prediction of shoreline movement to different parts of the coast. Hence the assessment of the susceptibility of the coast to observed and projected changes in metocean conditions has been undertaken for sediment cells that support different landform associations.

The degree of susceptibility has been estimated on a comparative basis as being low, moderate or high depending on the presence, extent and elevation of outcropping bedrock. At the broadest scale a river delta or barrier may not be susceptible to long-term change whereas elsewhere a different type of delta or barrier system may be highly susceptible. This is apparent when the perched barrier along the Dongara to Cape Burney shore (Cells 21 to 34) is compared to the coast between Cliff Head and Leander Point (Cells 18 to 21) which may have formed over a deeper rocky basement. A similar comparison may be made between the wave-dominated deltas of the Greenough and Chapman rivers with that of the Hill River in the Shire of Dandaragan. The disparity provides rationale for more detailed consideration of the geotechnical qualities of different systems.

Phases of dune activity through the Holocene are apparent as the nested blowouts and parabolic dunes which form the barrier ridge or the sequence of foredune ridges comprising the foredune plains of cuspate forelands, such as at Shoal Point. Small variations in dune activity identified from the photographic record used to examine the Areas of Planning Interest (Section 6) indicate the phases are associated with variation in the intensity and duration of metocean processes. In the long-term these will continue to contribute to development of the barrier ridge and migration of the point on cuspate forelands through the formation and destruction of foredunes, blowout activity and the migration of nested parabolic sand dunes, especially along parts of the shore susceptible to erosion.

High-level coastal limestone formations commonly stabilise the coast. However this generality does not always hold and areas of instability are found where unconsolidated sediments abut limestone outcrops, particularly those forming the boundaries of adjacent cells. Areas of significant instability also occur where the coastal limestone is low, as along the coast between Broken Anchor Bay and Bluff Point (Cells 54 to 60). Breaks in the nearly-continuous limestone ridge running parallel and along the shore of this part of the coast has resulted in the formation of small, elongate coastal lagoons, such as those at Horrocks Beach and Port Gregory.

Rise in sea level, whether a recurrence of historically extreme conditions due to storminess or a result of projected Global warming, potentially would trigger increased destabilisation of the foredunes and frontal dune belt along the shore. It would facilitate landward migration of the barrier where it is not perched on the coastal limestone. Barriers and cuspate forelands are viewed as being inherently unstable and require careful consideration in land use planning and management for this reason that. As O'Brien Planning Consultants (1987) noted from the coast between Dongara and Cape Burney, the most stable sections of the dune ridge comprising the barrier are the undulating swales of long-walled parabolic dunes on its landward side. However, these are not always in locations where access to the shore can be established without incurring ongoing maintenance costs for dune stabilisation and beach access management.

Roy *et al*. (1994) attributed the type of barrier found on wave dominated coasts to variation in continental shelf gradient and sand supply as well as the wave regime. The types identified ranged from (a) sediment poor areas of eroding coast where there was a continuing loss of sand onto a steep continental shelf to (b) transgressive dune barriers and a large sand supply from a low-gradient continental shelf. With notable variations their models are applicable to parts of the Mid-West Coast. South of Point Moore the coast between Ledge Point and Cervantes is a major sediment sink on the Swan Coastal Plain. Sediment transported along and across the inner continental shelf has supplied the nested blowouts and parabolic dunes which formed the transgressive barrier during the mid to late Holocene. However, extensive tracts of limestone reef, low bluffs and rock platforms outcrop intermittently along the coast, particularly between the Unsurveyed Point and Cliff Head (Cells 10 to 18). Together with the relative stability of the coast at present, these indicate substantial geographic variation in volumes of sediment moving alongshore and shoreward and bring into question the time scales at which phases of sediment loss and accretion are occurring.

There is apparent sediment deficiency north of Point Moore, particularly north of Glenfield where the offshore reef system closes with the coast and the topography of the inner shelf changes. Large cliffs are a feature of the northern sector of the Study Area. Except on the large salient sheltered in the lee of the lee of Houtmans Abrolhos, between Broken Anchor Bay and Red Bluff (Cells 54 to 62) the episodic transgressive barriers tend to be smaller, restricted to more local sediment sources, with localised blowouts and parabolic dunes overlying bedrock topography. Small lagoons such as those at Horrocks, Port Gregory along the coast between Sandalwood Bay and Yanganooka are indicative of barrier retreat. Extensive but low lying sand sheets are a common feature of the eroded barriers which now overly old lagoonal sediments.

Medium time scales are relevant to barrier changes occurring over decades and centuries. In this context, dune formation and migration along the coast is ultimately dependent on sediment supply from offshore and alongshore. Currently, shoreline change is highly variable along the coast between and within compartments and cells. From a management perspective the patterns of change will require resolution and description at local and site scales as part of any development proposal.

At sub-decadal time scales, interaction of modern metocean processes with the inherited geologic framework has two ramifications.

1. First, alongshore variation in beach erosion, foredune formation and dune development occurs as a result of the interaction, with the reaches of coast most susceptible to environmental change commonly being in close proximity to shoreline salients and extensive rock outcrops.
2. 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; Jones 2005). This implies that localised estimation of shoreline change is necessary and should be linked to geophysical determination of the distribution and elevation of the underlying limestone topography supporting the barrier at places where development is under consideration.

7.2. ADVICE

A precautionary approach was adopted for the purposes of this report in the absence of an existing policy for susceptibility and instability on mixed sand and rocky coast, such as that of the Mid-West coast. The approach involved an analysis of coastal vulnerability based on available information, including published descriptions of the relative susceptibility of coastal land systems to change with variation in metocean processes as well as the current stability of individual landforms comprising them. The vulnerability analysis is the first part of a more extensive risk assessment which would identify the processes of change in more detail; examine social and economic implications; determine the consequences of projected and existing patterns of coastal change; and plan and implement adaptation strategies. To some extent, some of the adaptation strategies are embedded in the guidelines of the State Coastal planning Policy (SPP 2.6) and these provide the principles and rationale for the advice arising from examination of vulnerability on the Mid-West Coast.

7.2.1. General Principles

General principles applied in framing the recommendations are as follows:

1. The State Coastal Planning Policy SPP 2.6 identifies a range of considerations for the determination of coastal setbacks. The first two factors identified are coastal erosion and landform instability. Both are related to the interactions amongst the metocean processes, geological framework, unconsolidated sediments and landforms comprising the morphodynamic system of the coast. Briefly, following Wright & Thom (1977) a basic tenet of the vulnerability assessment applied here is that if one component of the morphodynamic system changes the rest respond to some extent on the soft-rock coast of the Swan Coastal Plain.
2. The distribution and elevation of the coastal limestones and sandstones are significant in that the presence of rock invalidates the so called 'Bruun Rule' of erosion (Bruun 1962) which is commonly applied in setback calculations under the State Coastal Planning Policy SPP 2.6. This point was made by Bruun (1983, 1988) in his critical assessment of inappropriate applications of his 'rule'. However, the rocky topography provides the geological framework for the development of unconsolidated, sedimentary landforms and therefore is a major determinant of the susceptibility of the coast to changes in the metocean regime.
3. A secondary determinant of the susceptibility of a coastal land system is related to the volume of unconsolidated sediment comprising the landforms of the shoreface (Houser & Mathew 2011). Herein the principle followed is that the different types and dimensions of barrier systems, river mouths and limestone topography present along the coast are related to sediment availability. Although outside the scope of this report, this proposition warrants closer consideration, particularly with respect to the perched barrier systems common along the Mid-West Coast.
4. Conceptual models of beach type, barrier structure, dune typology and river mouth morphology developed elsewhere (Section 2.4) are broadly applicable to the south-west coast of Western Australia and identification of the relative stability or instability of coastal landforms.

7.2.2. Coastal Management Advice

Advice specifically pertaining to the coastal planning and management of each sediment cell is listed in Appendix E.

The advice for each cell follows the format outlined in Table 2-11 to ensure a consistent interpretation has been applied for planning and management purposes, and that it complies with established guidelines developed by the WAPC (2003), DPI (2006) and DoT (2010). More specific information on the integrity of the natural structures (susceptibility to change) and stability (instability) of landforms is obtainable through combined interpretation of the landform descriptions for each cell (Appendices C & D) and the criteria used to rate landform susceptibility and stability (Table 2-6 and Appendix E).

Detailed interpretation and advice has also been made for the ten Areas of Planning Interest in Section 6 above. These follow the same format as the analysis of the cells containing them.

More general advice is as follows:

1. Locally the elevation of limestone or sandstone underlying the beach and dunes directly affects the susceptibility of the coast to changes in metocean forcing and influences coastal stability. It is a factor that could be determined as a planning requisite prior to implementation of any development proposal involving the establishment of rural-urban infrastructure in areas where there are perched barriers and beaches.

2. There is a need to develop policy and guidelines related to the siting of infrastructure on cuspate forelands and barriers, especially the former.

    a. Cuspate forelands are particularly vulnerable and may require reconsideration of the methods used to determine setback to development on these landforms.
    b. Different types of barrier support different assemblages of dunes. It is advised that the determination of setback to development be tailored to the different types with a larger setback allowance for barriers that are notably susceptible to change due to metocean forcing.
    c. Further, it is suggested development on dune ridges and crests in green field sites initially be restricted in preference to development of more stable areas in dune swales not prone to marine inundation or flooding, as was recommended by O'Brien and Associates (1987) for the Dongara-Cape Burney Coast.

3. Overall, the seaward part of a barrier is highly susceptible to destabilisation by metocean forcing, which also means it is highly likely to be destabilised through land use pressures. This is a major problem on the southern flanks of cuspate forelands, such as those at White Point, Separation Point, Eagles Nest and Shoal Point. It is also a problem in areas where dune blowouts commonly occur at present, as at White Point, Nine Mile Beach, Cape Burney North, Sunset Beach, Horrocks Beach, and along the coast from Shoal Point to Bluff Point.

    a. Following the guidelines of the State Coastal Planning Policy (SPP2.6), it is advised that shore parallel development of infrastructure such as coast roads, car parks and buildings be minimised in the frontal dunes.
    b. Additionally, cells with an unstable (moderate or high instability ranking) require controlled beach access from the coastal hinterland.

4. A wide setback for growth and change in dune landforms may be appropriate in places where foredunes are missing or eroded, and where more than approximately 50% of the length of coast along the vegetation line on the backshore of the beach is influenced by active blowouts. The setback to development currently applied under the State Coastal Planning Policy (SPP 2.6) may be calculated from the landward extent of the mobile dunes on these reaches of coast.

5. Preliminary schedules in the State Coastal Planning Policy (SPP 2.6) are outlined for the calculation of coastal erosion allowance, but there is no corresponding information for the susceptibility of a land system to change due to metocean forcing or the overall instability of landforms comprising the system. It is advised that these two aspects of coastal vulnerability be addressed in any review of the policy guidelines.

7.3. INCORPORATION IN POLICY

The susceptibility of coastal land systems to projected changes in metocean forcing over a planning horizon of 100 years, and the stability of the landforms each system supports could be incorporated in existing State planning policies and guidelines (WAPC 2002, 2003; DPI 2006). Examples of susceptibility, instability and vulnerability rankings as well as their implications for planning and recommended planning guidelines are listed in Table 2-12. The rankings, their implications for land use and suggested guidelines for management are listed in Appendix E for each cell.

The analysis of compartments and cells is intended to provide a natural framework with potential for a variety of applications in coastal planning and management. In this context Geographic Information Systems (GIS) models of the cells may be populated with information at the user’s discretion and at appropriate spatial scales. Under the policy and guidelines provided by the State Government, possible applications depend on the information linked with cells as overlays or tables for comparative purposes as has been done in this report. Potentially, applications range from structured audits of coastal population associated with individual land systems or landforms, infrastructure, beach use and tourism activities to comparative assessment of different parts of the coast to geographically different hazards and risks.

Direction for coastal planning and management by the State and Local Government is provided in the Coastal Planning Policy for Western Australia (WAPC 2003). The policy supports strategic objectives for environmental, community, economic, infrastructure and regional development interests; particularly through the recognition of natural hazards and minimisation of risk to people and property. Application of coastal zone management is mainly directed through the State Coastal Planning Policy SPP 2.6 (WAPC 2003), the Coastal Protection Policy (DPI 2006) and Department of Transport (DoT 2010) recommendations for inclusion of sea level change projection in coastal planning. These policies contain specific reference to incorporation of coastal landforms and metocean processes in coastal planning and management. The reference provides a direct link to the hierarchy of coastal compartments and sediment cells and, through them to coastal planning at all levels.

The SPP 2.6 (WAPC 2003) promotes the establishment of coastal setbacks and foreshore reserves to achieve strategic objectives, with focus on the following:

- *Recognition of the dynamic nature of coastal environments and the consequences for coastal development and use.*
- *Avoidance or mitigation of the impacts of natural hazards through intelligent siting and design of infrastructure, based on ongoing scientific research.*

Through the SPP 2.6 (WAPC 2003) and the Coastal Protection Policy (DPI 2006) it is recognised that land developments may be adversely affected by a range of physical processes occurring at the coast, with three of the most common being:

- Coastal erosion or accretion;
- Coastal flooding; and
- Coastal landform instability.

In the SPP 2.6 (WAPC 2003) coastal flooding refers to the submergence of coastal lowland by marine incursion as well as flooding by rivers and streams. The two processes are not differentiated.

A general method for calculating a horizontal setback allowance for coastal erosion is outlined in the SPP 2.6. Calculation of coastal setback to development is most appropriate at more-detailed local area planning and site scales than the sediment cell scale adopted for this report. However, the principles of recognising coastal dynamics and avoiding adverse impacts incorporated in the policy are relevant to vulnerability assessment. They are applicable in assessment of flooding and landform instability. Although site specific, they loosely entrain consideration of the susceptibility of each site to potential change and its current state of stability. Typically applications of SPP 2.6 include identification of minimum development levels, or minimum reserve widths to cater for shoreline movement and changes in sand dune formations.

Where use of wide setbacks is not practical or subsequent shoreline change has significantly reduced a setback allowance the Coastal Protection Policy (DPI 2006) allows for development of protective structures. However, clear justification for protective works is required, and unacceptable adverse environmental, social or financial impacts to neighbouring areas must be avoided. Within this context, the effects of sand impoundment by a protective structure must be considered:

> "*The natural supply of littoral sand is a resource shared by all West Australians. Accordingly, those benefiting from future works or developments that change the natural supply of sand along the coast shall compensate for the change to that supply...*"

The points made in State coastal policy guidelines of the WAPC (2003), DPI (2006) and DoT (2010) provide direction for the recommendations arising from the vulnerability analysis in two respects. First, coastal development should not be proposed in areas where there is a high probability of adverse environmental and other impacts occurring that would require installation of protective works in the projected 'life' of the proposed development, especially on 'green field' sites. Second, the requirement to consider the impact of proposed development on sand impoundment necessitates determination of the coastal sediment budget at a scale commensurate with the scale of the proposed development.

Through its context in coastal policy guidelines the vulnerability assessment also provides insight into approaches that may be used in land use adaptation to projected climate change and rise in sea level. Different facets of adaptation may be considered. For example, in undeveloped areas where there is a higher than moderate level of risk the vulnerability analysis can be used to plan avoidance of sites with potential risks or incorporated in plans that include contingency measures should development be necessary. Second, in areas with established infrastructure the vulnerability analysis may be used to determine the suite of environmental problems requiring more detailed risk assessment and the incorporation of social and economic considerations.

7.4. FURTHER STUDIES

In addition to further studies required for hazard and risk assessment under the State Planning Policy 2.6 (WAPC 2003) requirement for them is founded the need to redress information gaps and for management purposes. Further studies have been outlined for each of the Areas of Planning Interest. They are outlined below.

7.4.1. Risk Assessment

This report is intended to be indicative rather than prescriptive and have application for strategic planning purposes. It focuses specifically on the current and potential changes to the geomorphologic features of the coast. In a more complete assessment of coastal hazard and risk the assessment should be extended to include descriptions of landform change associated with meteorologic and oceanographic variables as well as consideration of the social and economic factors at risk. Results reported herein thus provide a first step to the application of more detailed risk and coastal vulnerability assessment procedures, such as those described by Kay *et al.* (1996), Brooks (2003), Harvey and Nicholls (2008), Harvey and Woodroffe (2008) and Finlayson *et al.* (2009). It broadly establishes the first steps to a full risk assessment. Full risk assessments are recommended for developed areas, including the townsites, and areas subject to increasing use for tourism and recreational purposes.

Frameworks and guidelines for risk assessment previously have been applied in an assessment of risk to the sustainability of a coastal, natural-resource based industry by Ogburn & White (2009) and to coastal management in New South Wales by Rollason *et al*. (2010) and Rollason & Haines (2011). Both applications use the AS/NZS ISO 31000 risk assessment framework (Standards Australia 2009) to determine management outcomes in circumstances where there is considerable uncertainty and a lack of detailed data to describe coastal changes. Both describe circumstances relevant to vulnerability assessment for land systems and landforms along the Mid-West coast. A similar approach has been adopted in this report by using a combination of structure and condition to determine vulnerability of landforms to existing and projected changes in metocean forcing. The vulnerability estimates are subsequently linked to broad estimates of the likelihood of environmental changes occurring. Vulnerability rankings then may be used to establish consequence and risk tables for the coastal landforms for a more detailed risk analysis that is not undertaken in the context of this report. However, it does provide an indication of further information requirements.

Risk assessment is commonly is undertaken in an established framework, such as the principles and guidelines within AS/NZS ISO 31000 (Standards Australia 2009). Assessment provides an estimation of the likely consequences arising from occurrence of a hazardous event, ranging from insignificant to catastrophic outcomes. Estimations of the likelihood of the event occurring (Table 7-1) are based on limited experience with hazard identification, description and mitigation within the region of interest. The hazard estimates are used in consequence tables such as that presented by Australia Pacific LNG (2010) to examine the likelihood of health, safety and environmental consequences of different types of hazards (Table 7-2). They are prepared as part of Environmental Impact Statements (EIS) for major development proposals in Australia. The method subsequently enables the consequences of hazards impacting on the environment to be prioritised and considered in a full risk assessment. In this respect the framework provided by AS/NZS ISO 31000 guidelines (Standards Australia 2009) has relevance to the State Planning Policy 2.6 (WAPC 2003). Regardless of risk a full hazard and risk assessment is required for all development under existing State Government coastal planning and management policies.

Table 7-1: Probability Table Based on Metocean Forcing and Geologic Records (Source: Rollason *et al.* 2010)

Probability	**Likelihood**
Almost Certain	There is a high possibility the event will occur as there is a history of periodic occurrence
Likely	It is likely the event will occur as there is a history of casual occurrence
Possible	There is an approximate 50% chance that the event will occur
Unlikely	There is a low possibility that the event will occur. However, there is a history of infrequent and isolated occurrence
Rare	It is highly unlikely that the event will occur, except in extreme circumstances which have not been recorded historically.

Table 7-2: Health, Safety and Environment Consequence Categories for Critical and Catastrophic Levels of Risk (Source: Australia Pacific LNG 2010: p6)

	Impact to company personnel	Natural environment	Community damage/ impact/ social/ cultural heritage
Catastrophic 6	Multiple fatalities ≥4 or severe irreversible disability to large group of people (>10)	Long term destruction of highly significant ecosystem or very significant effects on endangered species or habitats	Multiple community fatalities, complete breakdown of social order, irreparable damage of high value items of great cultural significance. Adverse international or prolonged (>2 weeks) national media coverage
Critical 5	1-3 fatalities or serious irreversible disability (>30%) to multiple persons (<10)	Major off-site release or spill, significant impact on highly valued species or habitats to the point of eradication or impairment of the ecosystem. Widespread long-term impact	Community fatality. Significant breakdown of social order. Ongoing serious social issue. Major irreparable damage to highly valuable structures/items of cultural significance. Adverse national media coverage (>2 days)

Steps in the framework provided by AS/NZS ISO 31000 guidelines presuppose the availability of a wide variety of metocean, geomorphologic, social, cultural and economic information. Advisedly, collation of the physical information required for a full risk analysis would be based on a comprehensive review of available data to identify gaps and directed to enable:

- Detailed consideration of potential impacts of metocean processes (waves, winds, water levels, tropical cyclones and river discharge), including geotechnical survey (site assessment of elevation and coverage of underlying rock using drilling or other appropriate technique) where appropriate This is most likely to be where it affects elements or landforms with lower integrity of the natural structure or limited natural resilience.
- Determination of the potential impacts of extreme metocean events (such as storms) on these elements or landforms based on geological and historical (measured and surrogate) information as well as modelling of projected future extreme events.
- Identification of sediment sources, sinks and key transport pathways as a first step to determine the rate of coastal change and the potential impact of any proposed land through modification of the coastal sediment budget and its affect on the most unstable landforms.

7.4.1. Data Requirements

Data requirements include:

- Baseline coastal monitoring information such as shoreface and beach profiles should be collected for reaches of coast supporting infrastructure and where there is increasing use of the coast for tourism and recreational purposes where limited historic information is available. Specific recommendations for monitoring have been made for the Areas of Planning Interest at Port Denison and Geraldton.
- It is recommend LiDAR mapping of the inshore waters be completed to provide a wider context for available bathymetric information and provide a more complete

assessment of natural resources, including sediment availability and distribution. Detailed inshore bathymetry for management of the inshore is available for parts of the coast, particularly in the vicinity of townsites in the Study Area. This is a particular requirement for the area between Cape Burney South and Glenfield Beach.

- Coastal sediment budget information, including identification of sediment sources and sinks as well as determination of approximate volumetric rates of sediment transport is to be completed for the areas of Planning Interest as well as cells adjacent to areas proposed for industrial and/or tourism developments.
- Determinations of the elevation and coverage of underlying rock are required for sites supporting urban-rural development and infrastructure that may be located on unconsolidated sediments overlying bedrock surfaces. Full geotechnical survey using drilling or other appropriate technique is recommended for these sites.

7.4.2. Other Requirements for Management Purposes

Other requirements for management purposes include:

- Identification and costing of ongoing management requirements at developed sites as well as those proposed for development or increased land use.
- Determination of potential migration or retreat of unstable landforms and the potential impacts of landform change on existing and proposed development.
- Identification of costs and allocation responsibility for management of coastal protection and stabilisation works, such as engineered structures and sediment bypassing, for the adjacent coast, as well as for ongoing coastal monitoring, maintenance and management of the site.
- Strategies to respond to metocean events and other site disturbances of various frequencies and magnitudes.

8. References

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Glossary

	Term	Explanation
A	Alongshore	Marine and beachface processes operating along the coast are *alongshore* processes. The term alongshore also indicates direction.
	Arcuate shoreline	An *arcuate shoreline* is an embayed shoreline. In plan form the arc is concave to shoreward and may be a half-heart shape, occasionally referred to as a zeta-form, or semi-circular in form. The shape provides an indication of ocean processes affecting the shore of the embayment.
	Aspect	*Aspect* is the direction to seaward the coast faces. It is estimated in the centre of the coastal feature being examined and at right angles to the trend of the coastline in plan. The direction faced by the coast determines the prevailing and dominant metocean processes to which it is susceptible. For example, unsheltered NW facing coasts in the region are fully exposed to storms from that direction.
	Avulsion	*Avulsion* is the switching, or rapid migration, of a river channel location and abandonment of the prior channel. This behaviour may be common on large active delta systems.
B	Backshore	The most landward extent of bare, unvegetated beach is the *backshore*. It is a zone infrequently inundated by storm waves active during phases of extreme, higher-than-average sea-level conditions.
	Backbarrier	The most landward barrier landforms, particularly the coastal dunes furthest inland, sandflats and washover lobes extending into coastal lagoons are referred to as *backbarrier* features.
	Barrier	*Barriers* are relatively narrow strips of sand parallel to the mainland coast. The sands occur in distinct lenses deposited at a particular geological time, with the most recent barriers being formed during the Holocene, over the past 10,000 years. Landforms associated with barriers extend from the inner continental shelf include those of the active shoreface, beach and dunes along the coast. The suite of dunes comprising the landform may be referred to as *barrier dunes*.
	Beach profile	The beach profile is the cross-sectional shape of the beach from the seaward toe of the foredune or upper reach of wave action to the seaward limit of currents generated by breaking waves. In a seaward sequence the profile may include the following morphology: berm, beachface, step, trough, ripples and bar. It is comprised of several zones defined by the dominant processes, including the subaerial beach, swash zone, and nearshore zone.
	Beach rock	A friable to well-cemented sedimentary rock, formed in the intertidal zone.
	Beach type	Beaches are categorised according to their environmental setting and profile configuration. In the context of this report the first distinction is between beaches located in *sheltered* or *exposed* locations where the most common wave conditions are less or higher than 50cms. *Sheltered beaches* have profiles that are flat or rounded. Both exposed and sheltered beaches may overlie a rocky substrate. These are *perched beaches*.
	Blowout	In plan form a *blowout* has a parabolic form with a width greater than its length. Blowouts occur in partially vegetated foredunes. A *blowout* forms when a patch of protective vegetation is lost,

		allowing strong winds to "blow out" sand and form a depression.
C	Calcarenite	A limestone consisting predominantly of sand-sized carbonate grains.
	Cliffed dune	The seaward margin of a foredune or frontal dune may be cut by coastal erosion that results in the formation of a low sandy cliff.
	Coastal compartment	A coastal *compartment* is a component of the geological framework of the coast. It is an area of coast bounded alongshore by large geologic structures, changes in geology or geomorphic features exerting structural control on the planform of the coast. Compartments contain a particular Land System or landform association depending on the scale at which they are being described.
	Continuous reef	*Continuous reef* occurs where an unbroken line of reef extends parallel to the shore for at least the length of the coastal feature under consideration.
	Curvilinear (rounded) beach	Beaches in sheltered environments subject to a relatively high wave regime compared with other sheltered beaches may have an upwardly convex or concave beachface profile. These are curvilinear in form and may grade to a step at the seaward limit of the swash zone.
	Cuspate foreland	On the Central Coast of Western Australia *cuspate forelands* are triangular-shaped accretions of sand extending seawards in the lee of an offshore reef. *Cuspate forelands* principally develop in response to longshore movement of sediment and hence are highly susceptible to changes in metocean processes.
D	Discontinuous reef	*Discontinuous reef* occurs where the line of reef extending parallel to the shore has gaps or breaks over the length of the coastal feature under consideration. The length of gaps along the coast under consideration is significantly less than that occupied by reef.
	Dissipative beach	A *dissipative beach* is one in which wave energy is substantially expended as the wave moves from its break point to the shore. Multiple lines of breakers are present. On an exposed wave-dominated coast wave heights exceed 2.0m and the profile includes a flat beachface with multiple bars and troughs in the inshore zone. In a sheltered environment where wave heights are less than 0.25m the profile is planar, with a very broad sub-tidal terrace.
	Division	A *division* is a subdivision of a broad climatic zone. The unit provides an overview of the whole state suitable for maps at scales of about 1:5,000,000. For example, wet-dry tropics and sub-tropical areas are subdivisions of the tropical zone in north Western Australia.
E	Eolianite	*Eolianite* is weakly cemented rock that is commonly comprises calcareous dune sand derived from a marine environment. The stratigraphy of the dunes in which the eolianite has formed is usually present in outcrops.
	Episodic, transgressive dune barrier	An *episodic, transgressive dune barrier* comprises nested blowouts and/or parabolic dunes. The dunes commonly form a ridge of irregular height along the coast. The ridge and its dunes are the surface features of the barrier which also extends offshore as a marine deposit of sands with a similar mineral composition to those found in the dunes.
	Exposed beach	*Exposed beaches* are open to the full effects of metocean processes. The beaches experience average wave heights of over 1 metre and are considered to be wave dominated. They have reflective, transitional or dissipative profile features.
F	Flat beach	*Flat beaches* occur in very sheltered environments, those with a

		modal wave height of less than 25cms. The beach profile is likely to have a negative exponential shape with a small, narrow, upwardly concave beachface grading to a flat low tidal and wide intertidal terrace that terminates in a steep drop to deep water.
	Foredune	A *foredune* is a small coastal dune or low ridge. Foredunes are commonly less than 10m in elevation, located parallel to the shoreline and along the landward margin of a beach and stabilised mainly by pioneer vegetation. Foredunes are built through pioneer vegetation trapping of windblown sand directly from the beach. They build in height until the vegetation is destroyed; blowouts are formed and migrate landwards.
	Foreshore	The *foreshore* of a beach includes the berm, swash zone and lower intertidal zone.
	Frontal dune	Blowouts and parabolic dunes closest to the shore and immediately landward of the backshore where foredunes have formed or potentially could form are the *frontal dunes* or *primary dunes*. Absence of a foredune supporting pioneer species and scarping (cliffing) of the frontal dunes is indicative of a depleted sediment supply and coastal erosion.
G	Geologic framework	The *geologic framework* of a coastal area is the surface topography or geometry of bedrock in a designated area that interacts with metocean processes and the sediment transport regime to affect the distribution of unconsolidated sediments and the development of coastal landforms.
H	Hind Dunes	*Hind dunes* are those landward of the frontal or primary dunes.
	Holocene	The *Holocene* is a geological epoch that began approximately 12,000 years ago. It is an interglacial period of atmospheric warming and sea level rise. During the last 10,000 years before present sea level rose from below 50m to a peak of 1 to 2 metres above its present level approximately 6,000 years ago. The modern coast developed in response to this rise and subsequent fall.
I	Inshore	In the context of this report the term *inshore* refers to waters and seabed less than 25m deep adjoining the shore. The area commonly includes offshore reefs and the lagoons they impound.
	Instability	*Instability* refers to the current condition of similar landforms from different places. For example, it may be apparent as the percentage of vegetation cover on different dune fields, the completeness of foredune development on sandy beaches or differences in the historical records of shoreline movement on beaches.
	Isobath	An *isobath* is a submarine contour line indicating points of equal depth on a bathymetric map.
	Intermittent reef	*Intermittent reef* occurs where outcrops are uncommonly distributed in waters along the coastal feature under consideration.
J		
K		
L	Lagoon	A coastal *lagoon* is a water body sheltered from the full impact of oceanographic processes by an offshore reef or dune barrier.
	Land system	A *land system* is an area of characteristic landform patterns suitable for mapping at regional scales of 1:50,000 to 1:100,000. Several landforms form a landform pattern which in turn comprises a land system.
	Landform	A *landform i*s a natural feature of the Earth's surface. Landforms range in size from small features apparent at a local scale to large structures apparent at a land system or regional scales. In the context of this report the term is used to describe features apparent

		at a local scale of 1: 500 to 1:25,000.
	Landform association	A *landform association* is a group of contiguous landforms that are associated in some way, commonly by shared location or age structure. For example, a Holocene sandy beach perched abutting an older dune and perched on a Pleistocene limestone platform..
	Landform element	Each landform is made up of geometrically recognised components or *landform elements*. For example a blowout dune includes a slack, side walls, dune crest, slipface and toe slope.
	Landform pattern	A *landform pattern* is a group of landforms of a common geologic age that is the landform part of a land system. For example, a Holocene progradational barrier (landform system) is a low-lying plain (landform association) comprised of a sequence of foredune ridges, a beach and shoreface morphology.
	Littoral	The adjective *littoral* is used to designate the beachface and adjoining inshore areas of a sandy beach as well as the processes affecting them. The *littoral zone* extends from the spring high tide line to submarine areas affected by swash processes.
M	Mainland beach	Mainland beaches are apparent where a thin deposit of marine sands abut Pleistocene or older landforms. In some instances the sand may be subtidal and abut a platform or cliff.
	Metocean	*Metocean* is an abbreviation of meteorological and oceanographic. Hence *metocean processes* include all atmospheric and oceanographic processes such as storms, winds, waves, currents and tides.
	Mobile dunes	*Mobile dunes* are apparent as partially vegetated and open sand masses associated with blowouts, parabolic dunes and sand sheets.
	Morphodynamic	The coastal system is one in which morphology, sediments and processes are dynamically linked such that change in one will be associated with change in the others. This is referred to as a *morphodynamic* system.
	Morphostratigraphic	The term *morphostratigraphic* is used to indicate linkages between coastal morphology and stratigraphy.
	Morphology	*Morphology* describes landform assemblages or systems comprised of unconsolidated sediment.
N	Natural Structure	*Natural structures* are geologic or geomorphological features, such as a rocky prominentry or a sandy barrier.
O	Offshore	The term *offshore* is used in the report to designate either ocean seaward of the 30m isobath or shallower water seaward of the zone in which waves break.
P	Parabolic dune	In plan, a *parabolic dune* is a long U-shaped dune with long trailing arms (the vertical part of the U) pointing to windward. Parabolic dunes are common in the Central West Coast Region, where dune migration commonly occurs over a low plain or flat marl surface.
	Pavement	*Pavement* is a rock surface outcropping at an elevation close to the surrounding seabed. It may be part of a mixed sand and rock seabed, or patched reef, where it is irregular in form and elevation.
	Perched beach	Sandy beaches on which the sand overlies a rock pavement, beachrock ramp or rock platform is referred to as *perched beaches*. Under an engineering definition beaches immediately landward of a rock outcrop but separated from it by a narrow lagoon may also be classed as perched beaches.
	Pioneer vegetation	Herbaceous and grassy vegetation that first colonises the storm wrack line along the backshore as well as disturbed sites in dunes to landward is *pioneer vegetation*.
	Platform	A gently sloping surface produced by wave erosion, extending into

		the sea from the base of a wave-cut cliff.
	Pleistocene	The *Pleistocene* is the first geological epoch of the Quaternary Period and spans geologic time from approximately 2.6 million to 12,000 years before present. It is a time of repeated glaciations and sea level fluctuation on Earth.
	Pocket beach	A *pocket beach* is a small beach fixed between two headlands. Pocket beaches are commonly crescentic in plan, with the concave edge toward the sea. There is very little or no exchange of sediment between the beach and the adjacent shorelines.
	Prograded barrier	A succession of multiple foredune and/or beach ridges on the open coast and in sheltered waters form low-lying plain referred to as a *prograded barrier*. The plain may be features of a composite barrier where they merge with transgressive dune fields to landward or are overlain by blowouts along their seaward margin.
	Province	A *province* is an area defined on geological (lithology, topography and stratigraphy) or geomorphologic (major land systems) criteria suitable for a regional perspective at a scale of about 1:1,000,000. Originally described by CSIRO (1983).
Q	Quaternary	The *Quaternary* Period is the most recent of the three periods of the Cenozoic Era in the geologic time scale and has extended from approximately 2.6 million years ago to the present. The Quaternary includes two geologic epochs: the Pleistocene and the Holocene Epochs
R	Receded barrier	On coasts where sediment supply is limited *receded barriers* are thin marine sand deposits in narrow dunes that overlie estuarine, backbarrier or mainland features which outcrop at the shore.
	Reef	In the context of this report the term *reef* refers to any rock outcrop with an elevation above the surrounding sea bed. Herein, reef is described as being *continuous, discontinuous* and *intermittent* or as *pavement.*
	Reflective beach	A *reflective beach* is one on which incident waves are reflected seaward from a steep beachface following backwash run out. Reflective beach profiles are characterised by a berm or berms, a steep beachface, a step at the bottom of the swash zone and a deep, planar inshore zone. They are common features of coasts with a modal wave height of approximately 0.5 to 1.5 metres but also are observed on beaches comprised of coarse sediment and subject to larger waves.
	Region	A *region* is an area with a characteristic pattern of land systems that differentiates it from adjacent areas. The unit is suitable for mapping at scales of approximately 1:250,000. This differs from the definition provided by CSIRO (1983) and Schoknecht *et al.* (2004).
	Rhythmic shoreline	An uninterrupted sandy shoreline is considered to be *rhythmic* when it has a sinuous plan form with shallow embayments separated by shoreline salients.
S	Salient	Part of a sandy coast protruding seaward of the average trend of the shoreline.
	Sand sheet	A *sand sheet* is either a mass of mobile sand that has become detached from a blowout or parabolic dune and is moving freely across the landscape; or it is an area of bare sand where active blowouts and/or parabolic dunes have coalesced.
	Sediment cell	A coastal *sediment cell* is a section of coast and its associated nearshore area within which the movement of sediment is apparent through identification of areas which function as sediment sources, transport pathways and sediment sinks. Classically, interruptions to movement of sediment within one cell

		should not affect beaches in an adjacent cell. However this is not always applicable to beaches in Western Australia where the major source of sediment is derived from offshore sources.
	Sheltered beach	*Sheltered beaches* are protected from the full effects of metocean processes by offshore reefs or by their aspect. The beaches frequently experience average wave heights of less than 1 metre and are considered to be dominated by fluctuations in sea level, particularly those associated with surge. They have flat profiles which may be segmented where longshore currents prevail, or rounded profile features under wave regimes relatively higher than those experienced on flat beaches.
	Shoreface	The *shoreface* is a zone extending seaward from the foreshore, beyond the breaker zone to the limit of wave movement of sediment. It is the zone in which the majority of sediment transport occurs.
	Shoreline	The shoreline is a discrete line along the coast. In the context of this report it is the High Water Line used in the Australian Oil Spills Response Atlas (OSRA) and described by Landgate (2006).
	Shoreline plan	The *shoreline plan* is a view of the shoreline shape from directly above so that its plan shape is readily apparent.
	Straight shoreline	A *straight shoreline* closely approximates a straight line over the length of coast under consideration.
	Stationary barrier	*Stationary barriers* are narrow, capped by blowout dunes overlying well developed backbarrier sandflats and washover lobes. Stationary barriers are commonly associated with coastal lagoons or adjoin alluvial flats to landwards.
	Stratigraphy	*Stratigraphy* is the study of geologic strata or layers of sediment.
	Substrate	The *substrate* is the surface on which a barrier sits. For example, the Holocene barriers forming the modern coast are commonly located on a coastal limestone surface of Pleistocene age.
	Susceptibility	*Susceptibility* is an estimate of the likelihood of a land system altering in structure over a planning horizon of 100 years. The estimate is based on a comparison of the existing structure with reported descriptions of the evolution of similar structures. Following Roy *et al.* (1994) for example, prolonged erosion of an episodic transgressive barrier complex may result in a change to a receded barrier.
	Swash	Swash describes the uprush and backwash of waves on the beachface of a sandy beach. The swash zone extends seaward from the limit of uprush down slope to include the step at the bottom of the beachface and the inshore area affected by backwash run out.
T	Time scales	The *long-term* times scale refers to coastal evolution and the *susceptibility* of land systems to change over geologic time, particularly over the geological epochs of the Quaternary Period; the Pleistocene and Holocene Epochs. The short-term time scale refers to factors affecting the *stability* of coastal landforms. These are linked to the 100 year planning horizon of the State Coastal Planning Policy (SPP 2.6) as follows: *Short-term*: 1 to 10 years *Intermediate-term*: 11 to 25 years *Long-term*: longer than 25 years
	Tombolo	A *tombolo* is a deposition landform in which an island is attached to the mainland by a narrow piece of land. Tombolos are developed by refraction, diffraction and longshore drift to form a spit or bar that connects the mainland coast to connecting a coast to an offshore

		island. Once attached, the island is then known as a tied island.
	Topography	In the context of this report t*opography* describes landform assemblages or systems comprised of rock
	Transgressive dunes	Blowouts and/or parabolic dunes migrating landward from the sediment source at the beach are *transgressive dunes* in that they bury older landforms (and infrastructure) as they migrate. Dune mobilisation takes place episodically hence the dunes may be overlain to form and episodic, transgressive barrier.
	Transitional beach	On exposed, wave-dominated coast sandy beaches may fluctuate in form between reflective and dissipative states as the wave regime alters between low and high wave extremes. Between these extremes the *transitional* state is one with profiles that have elements of both. Transitional sandy beaches are morphologically characterised by bars, troughs and rip current channels.
U	Unconsolidated sediments	*Unconsolidated sediments* are loose sediment particles such as gravel, sand, silt and clay that have not been lithified or consolidated into rock.
V	Vegetation cover	For a designated area *vegetation cover* is the proportion of the land surface covered by plants.
	Vulnerability	*Vulnerability r*efers to the likelihood of a land system or landform changing in response to changing metocean conditions. It is estimated as a combination of the long-term susceptibility and short-term instability of a coastal compartment or sediment cell.
W	Washover lobe	Under extreme storm conditions and high sea levels low barriers may be breached by waves that wash sediment from the beach onto lowland or into lagoons landwards of the barrier. The sediment is deposited in fans or *washover lobes.*
X		
Y		
Z	Zone	*Zone* has two meanings. Firstly, in a land system context it is a broad section of the Australian Coast based on climate, and separating the tropical from temperate zones. These are referred to as regions by CSIRO (1983) and Schoknecht *et al.* (2004). Secondly, at a more detailed scale zone describes a small area where a particular suite of coastal processes and landforms are present. For example, the nearshore zone is where waves, wave driven currents and tides determine the pattern of bars and beach shape.

Appendix A Coastal Landforms: North Head and Nuningjay Spring Coast North

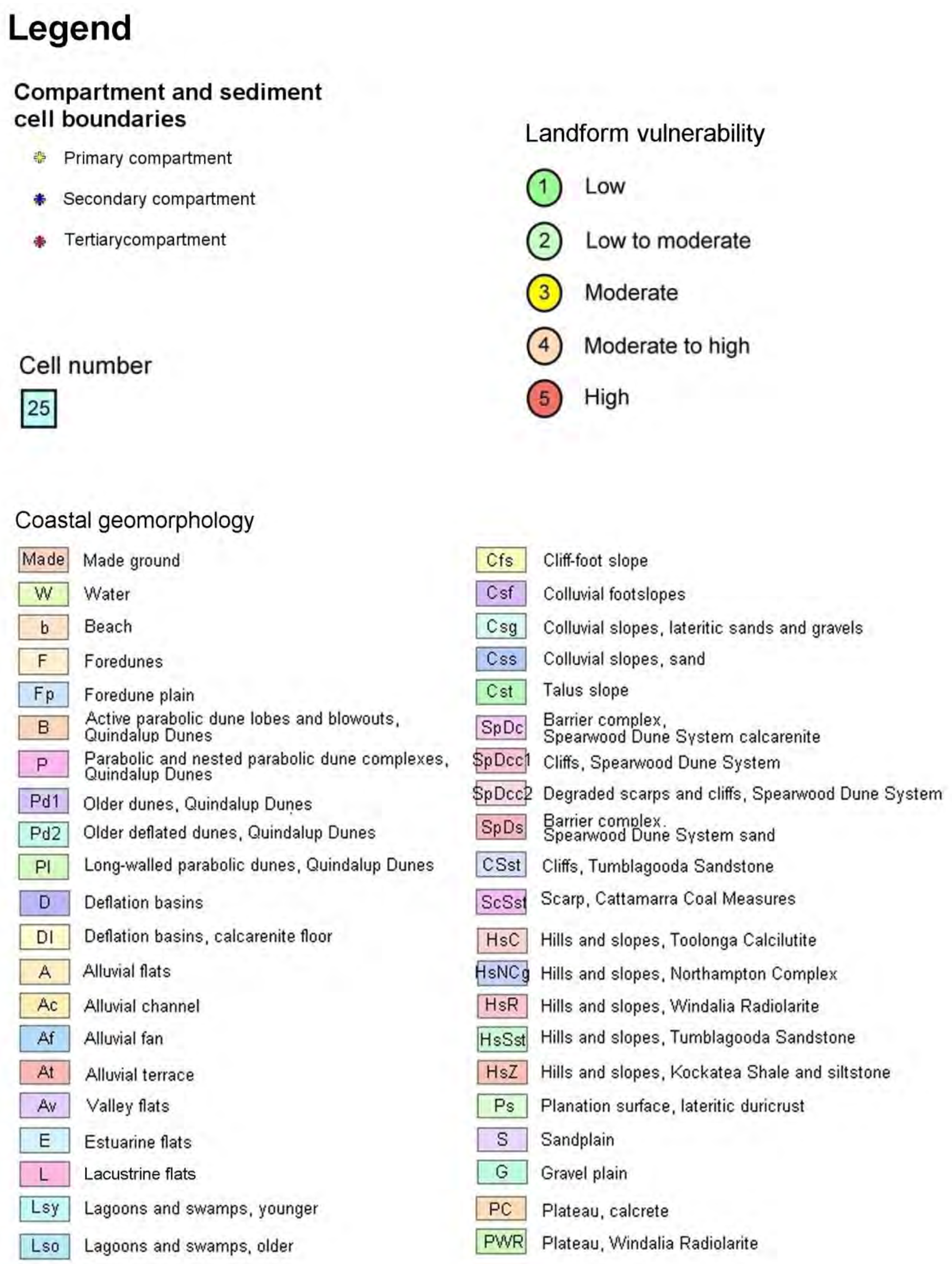

Figure C - 1: Compartment, Cell and Landform Map Legend

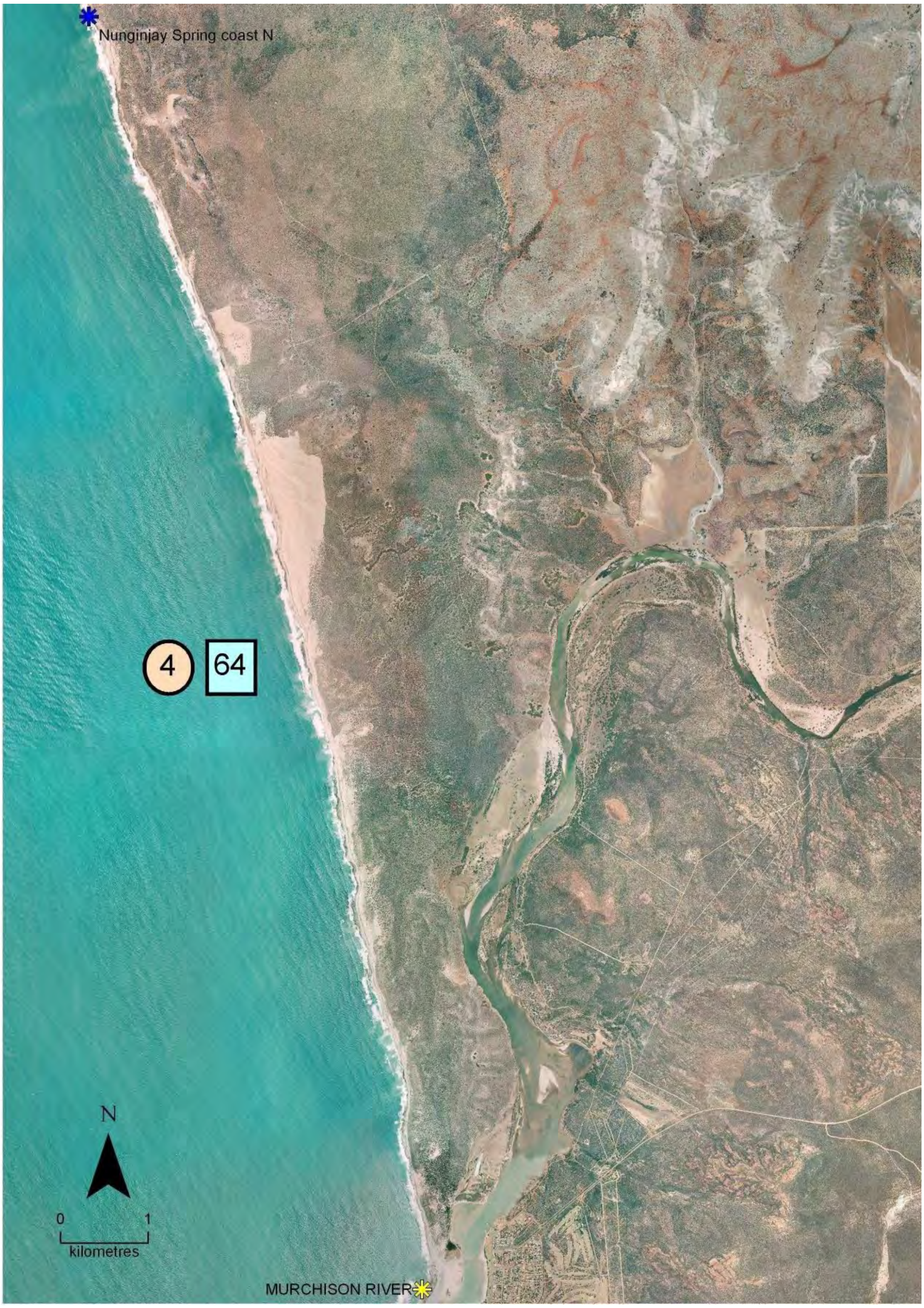

Figure C - 2: Vulnerability for Cell 64

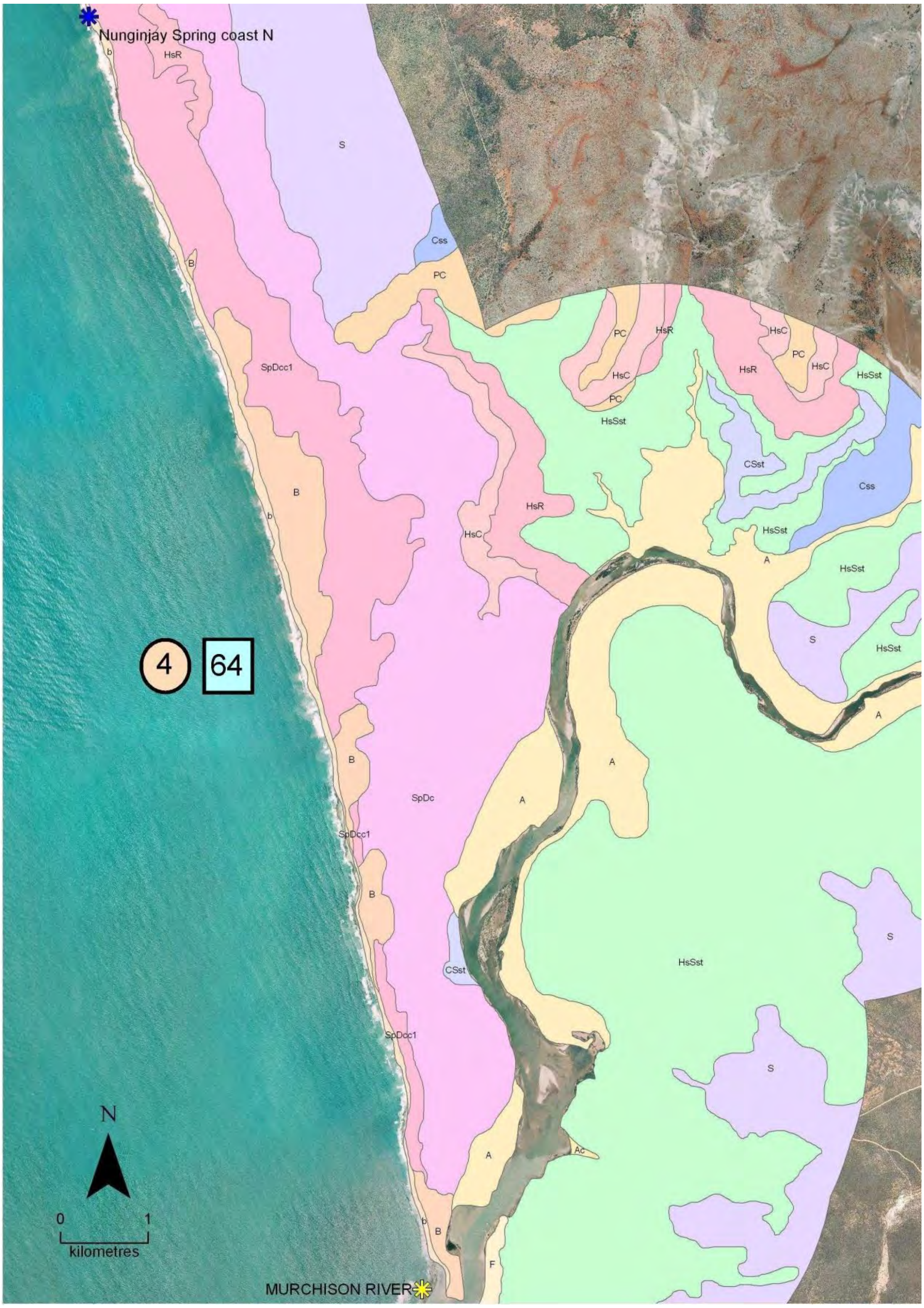

Figure C - 3: Landforms for Cell 64

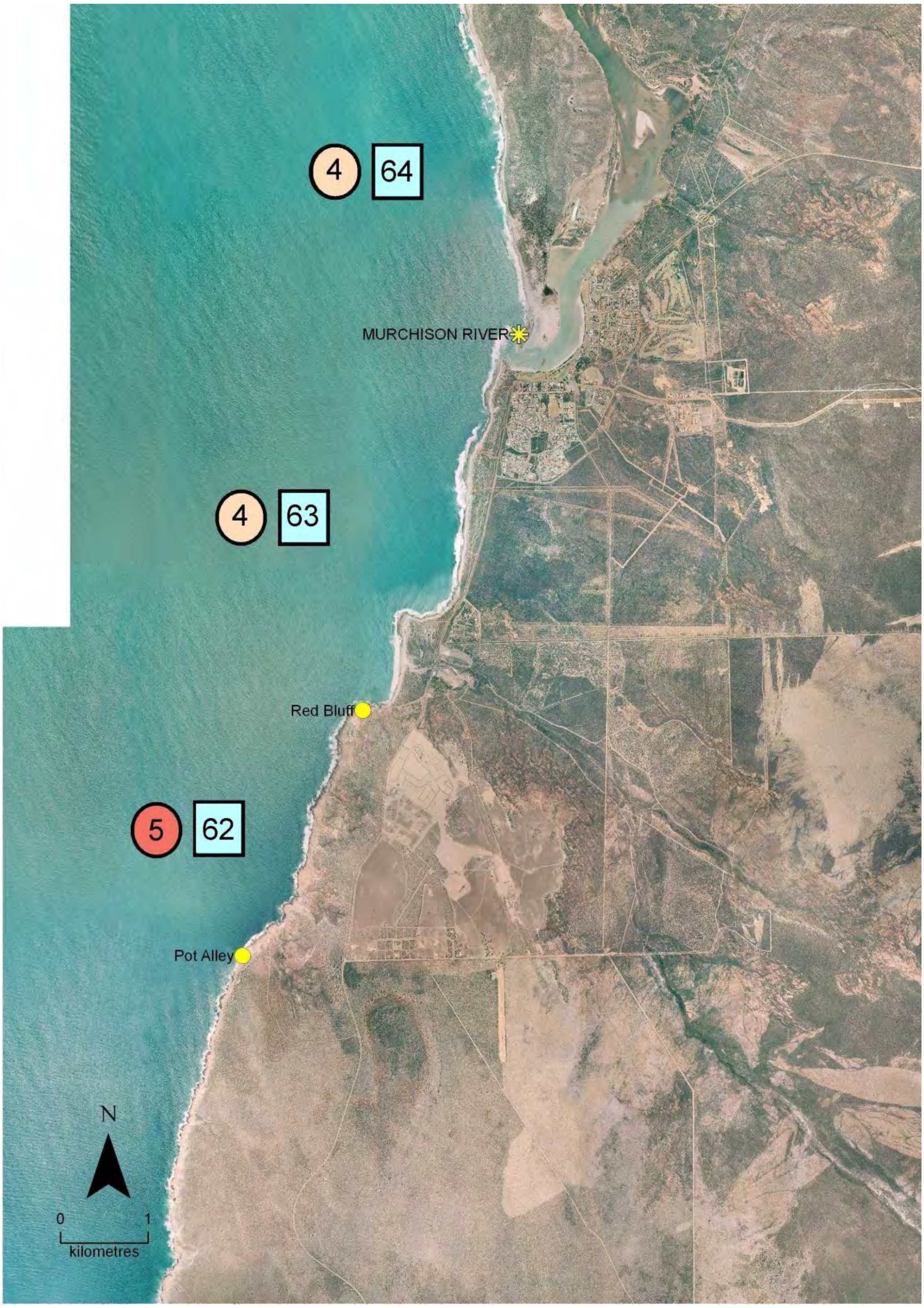

Figure C - 4: Vulnerability for Cells 64-62

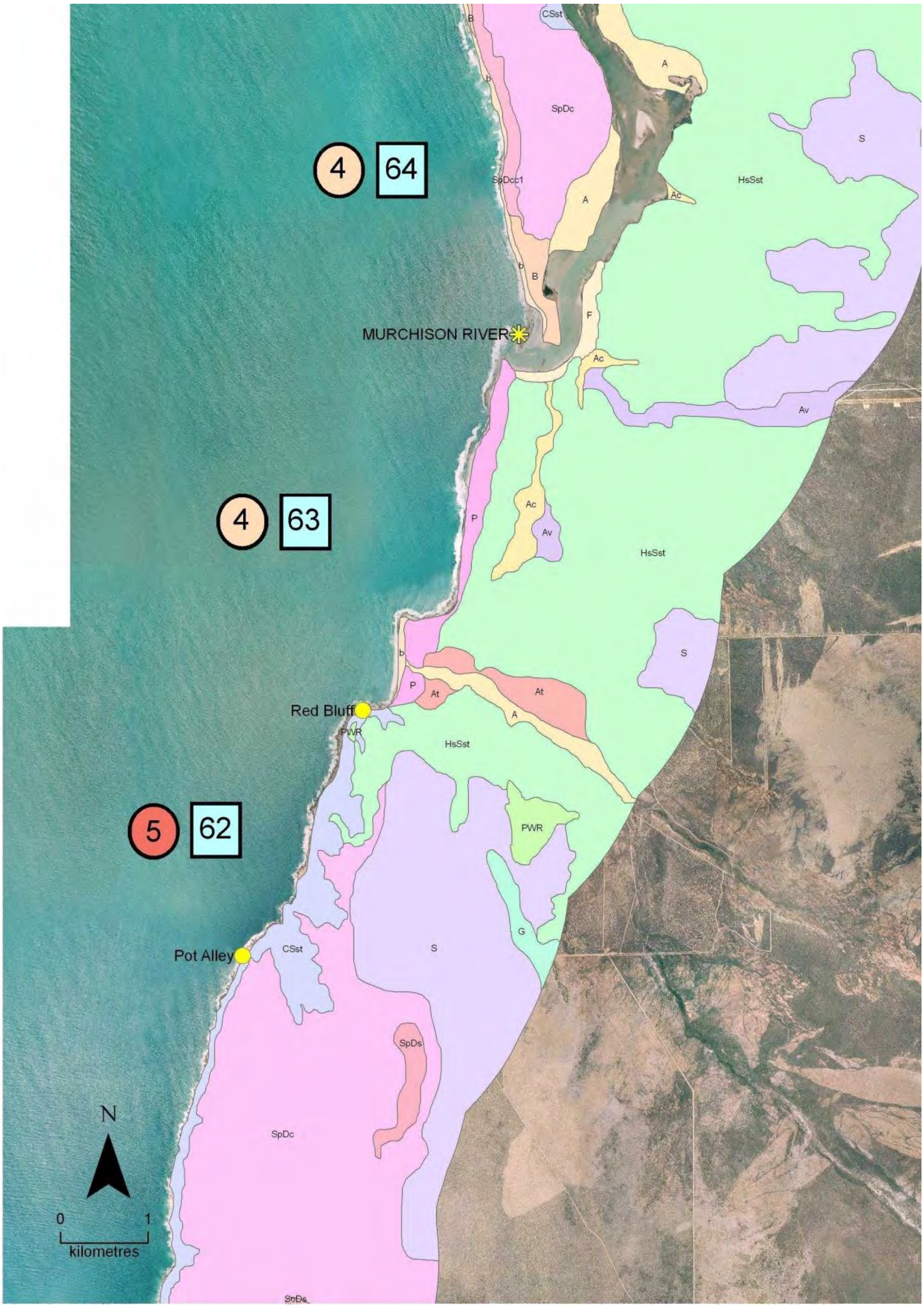

Figure C - 5: Landforms for Cells 64-62

Figure C - 6: Vulnerability for Cell 61

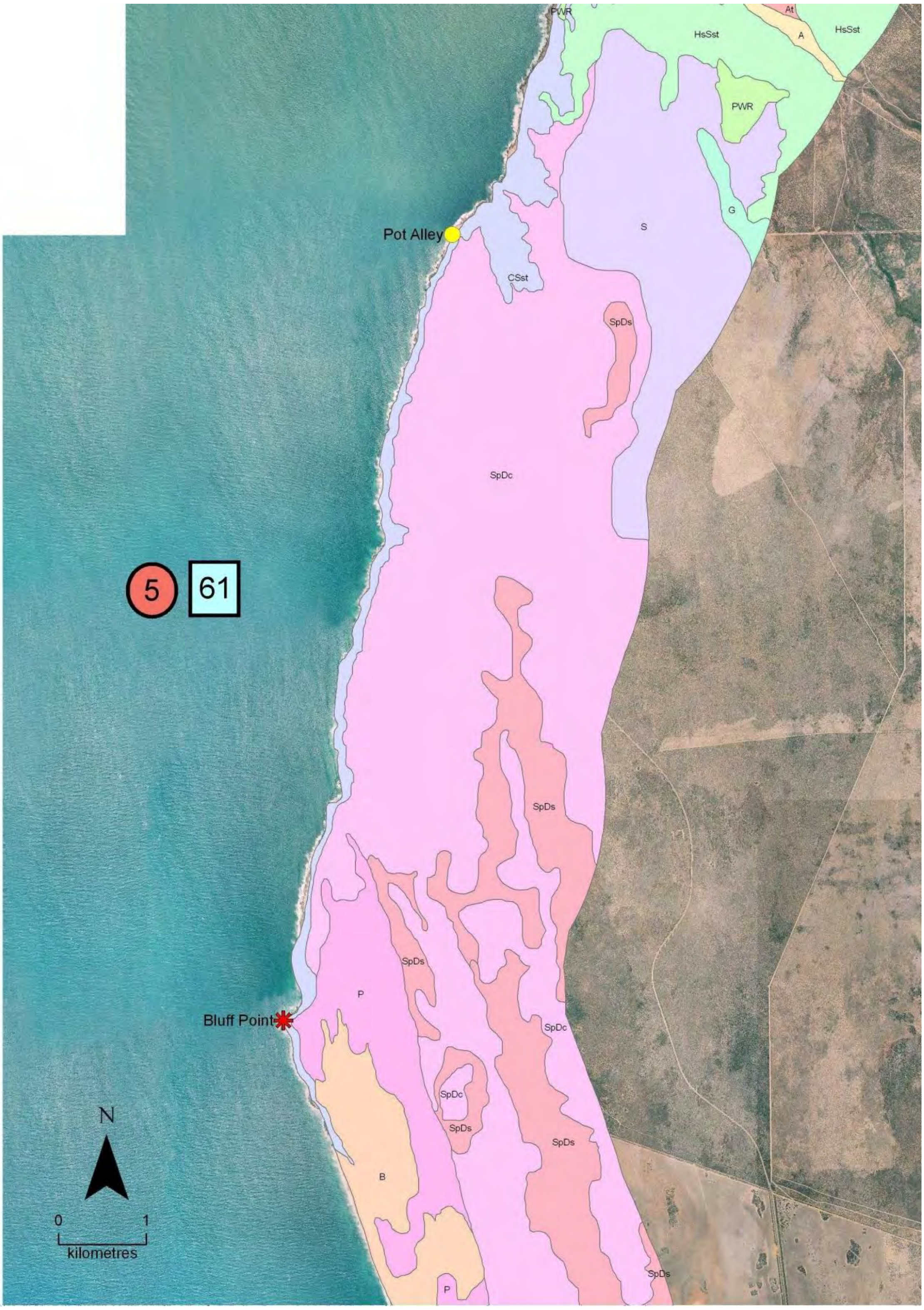

Figure C - 7: Landforms for Cell 61

Figure C - 8: Vulnerability for Cells 59-60

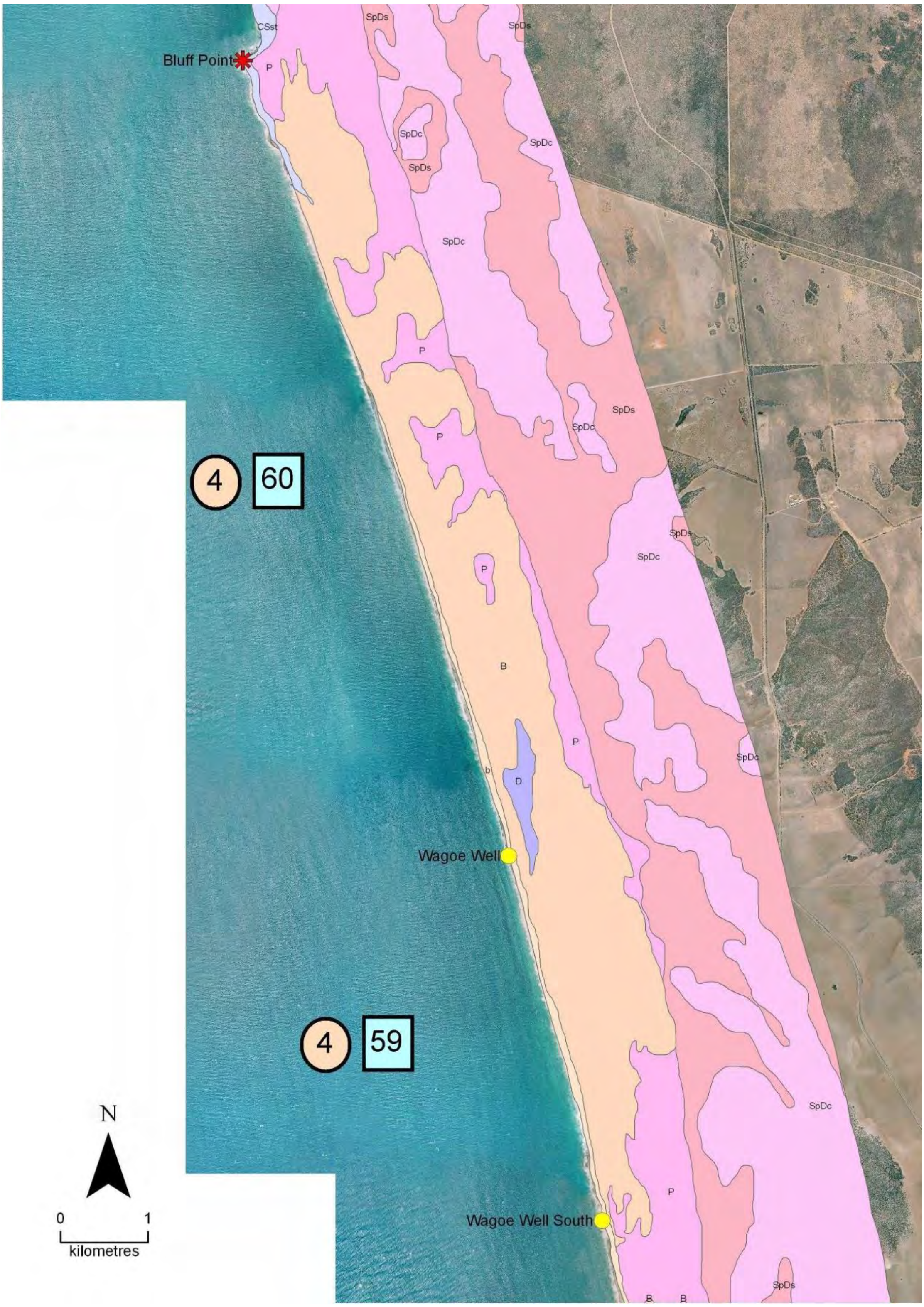

Figure C - 9: Landforms for Cells 59-60

Figure C - 10: Vulnerability for Cells 57-58

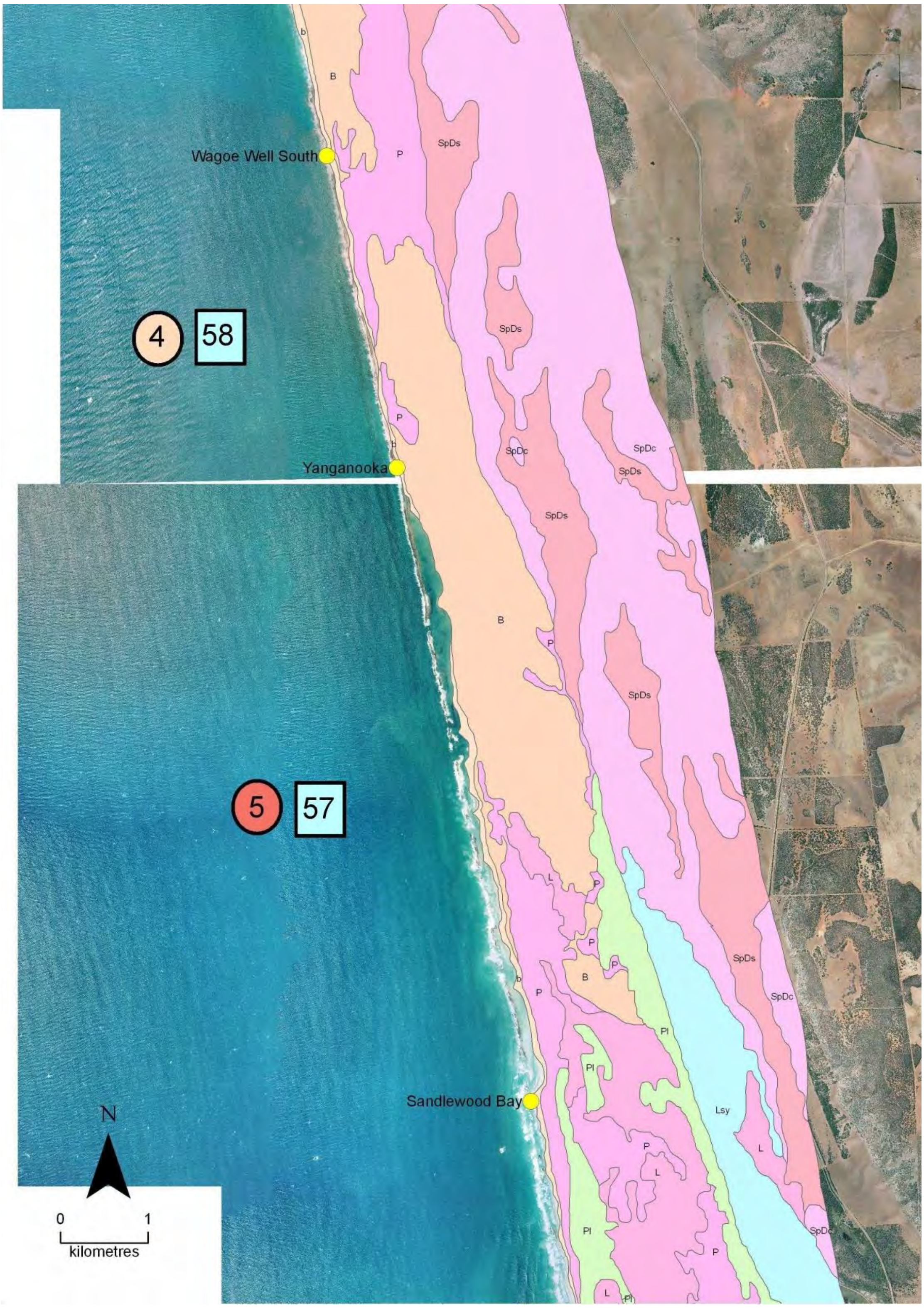

Figure C - 11: Landforms for Cells 57-58

Figure C - 12: Vulnerability for Cells 55-56

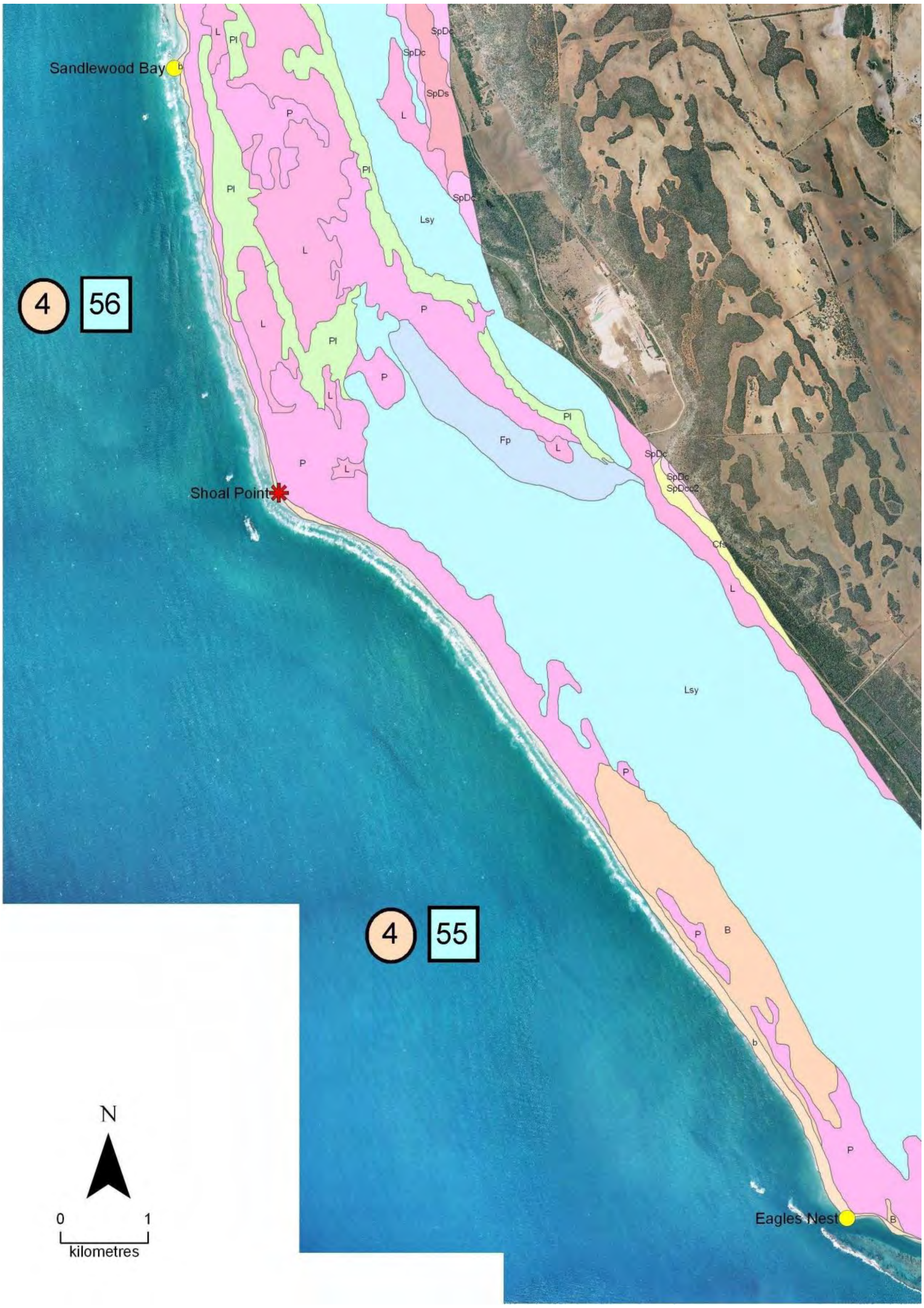

Figure C - 13: Landforms for Cells 55-56

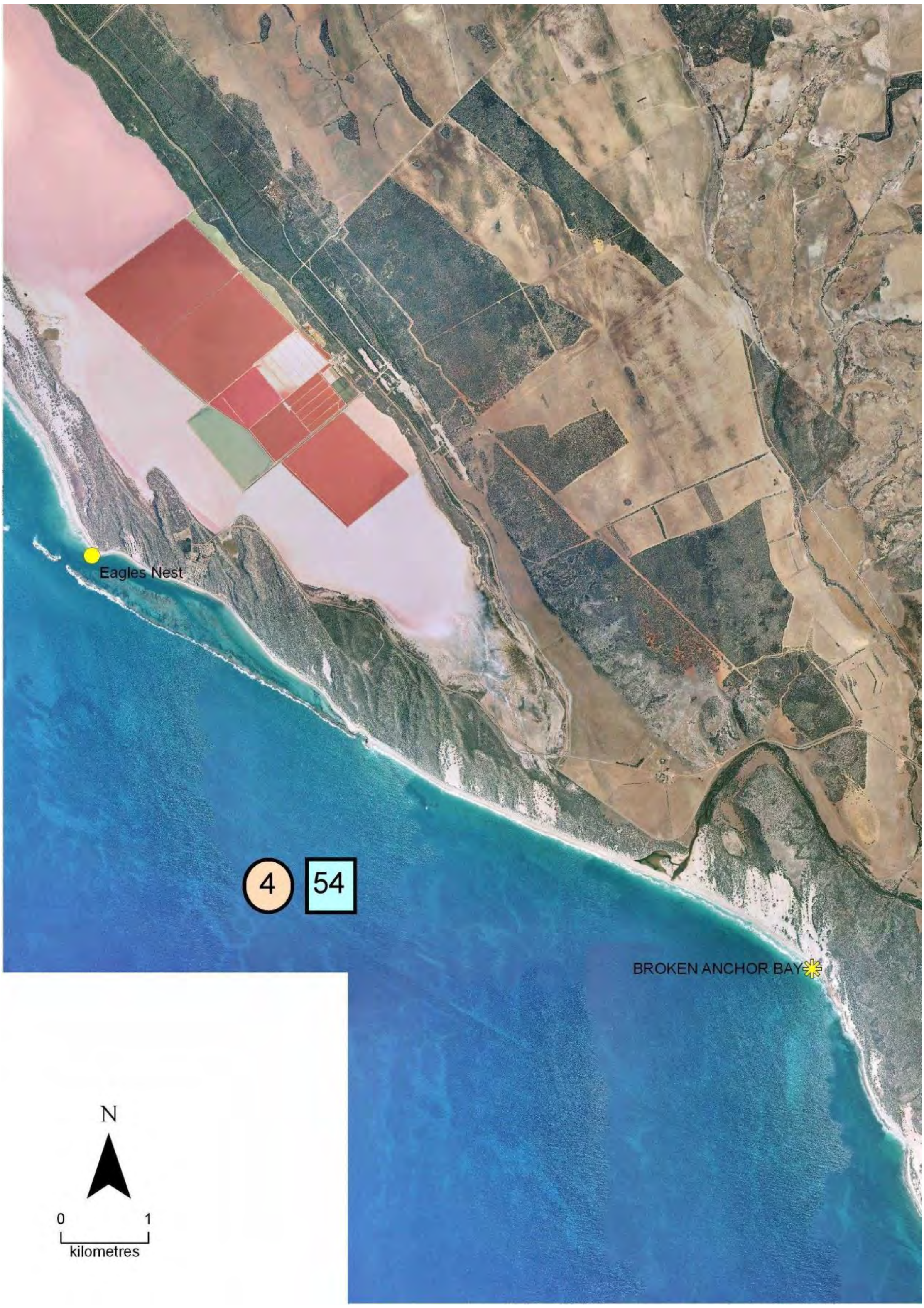

Figure C - 14: Vulnerability for Cell 54

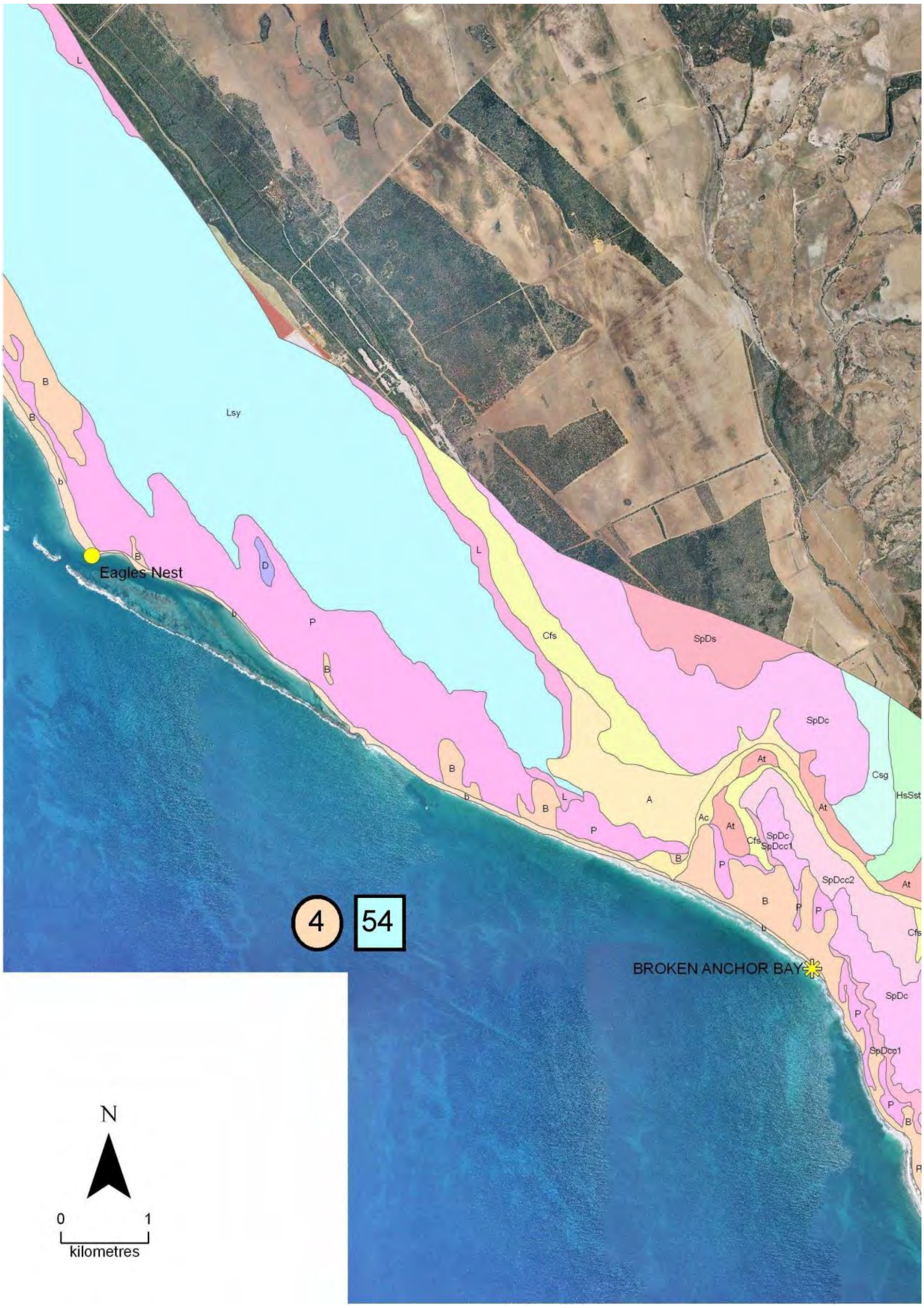

Figure C - 15: Landforms for Cell 54

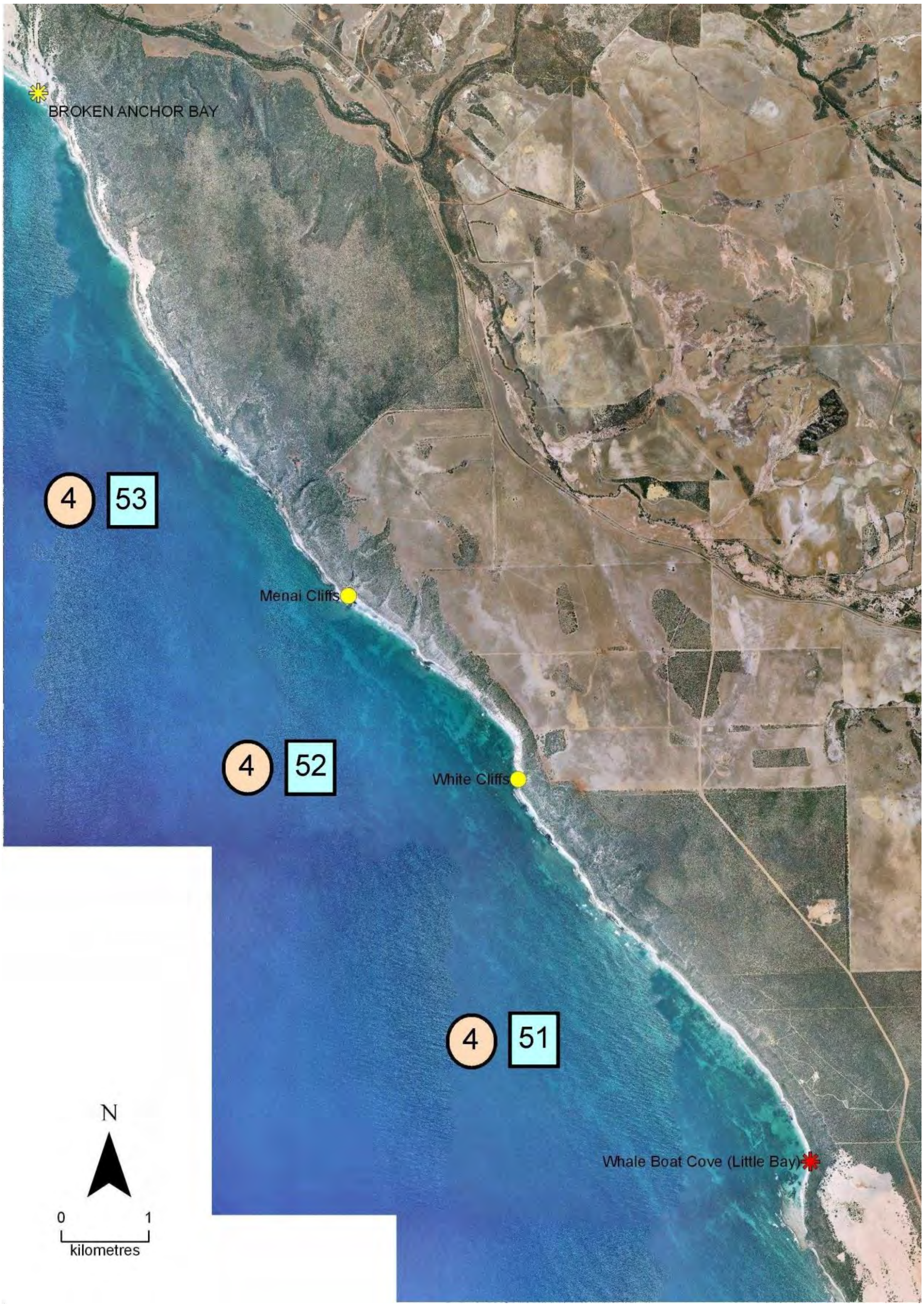

Figure C - 16: Vulnerability for Cells 51-53

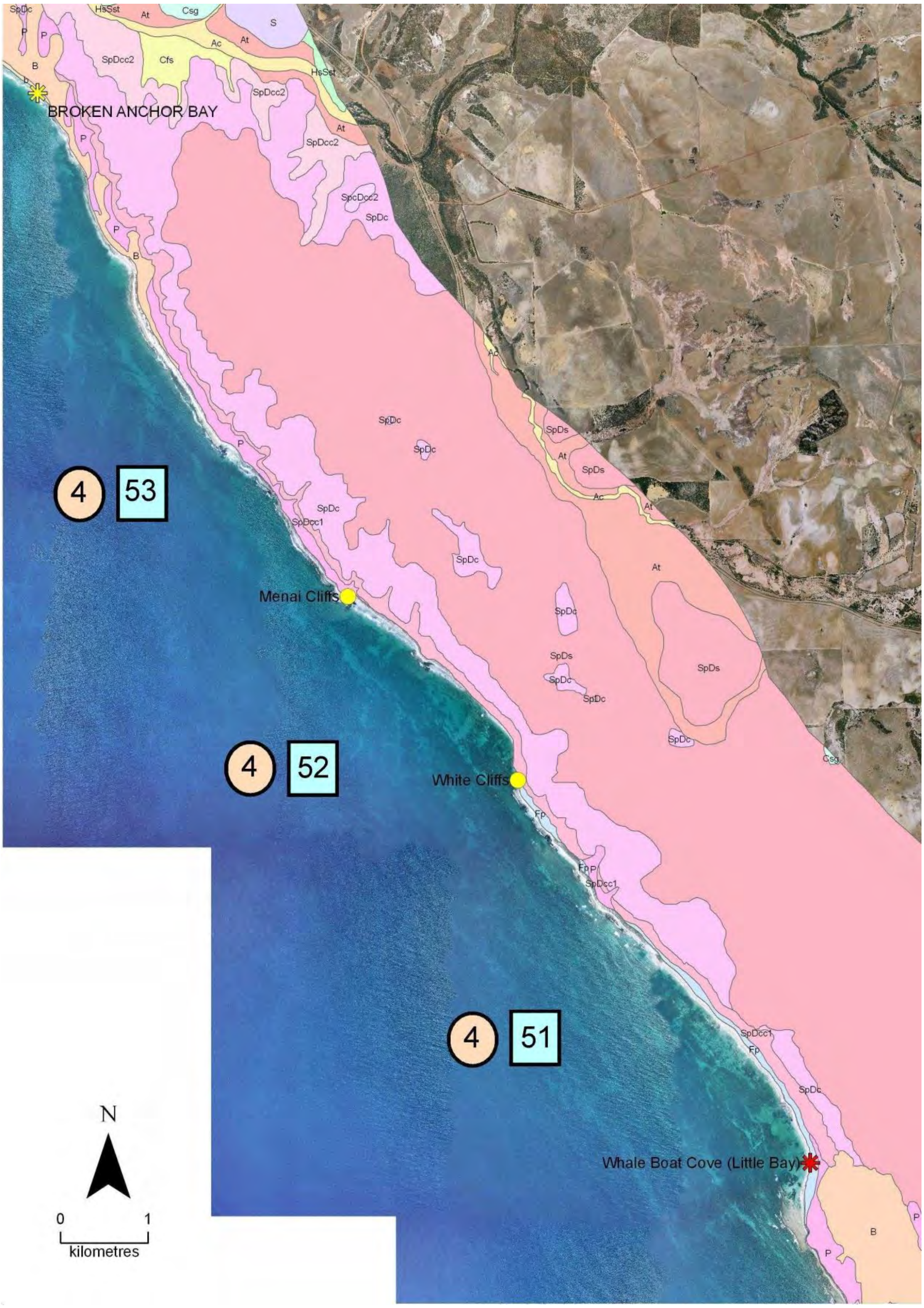

Figure C - 17: Landforms for Cells 51-53

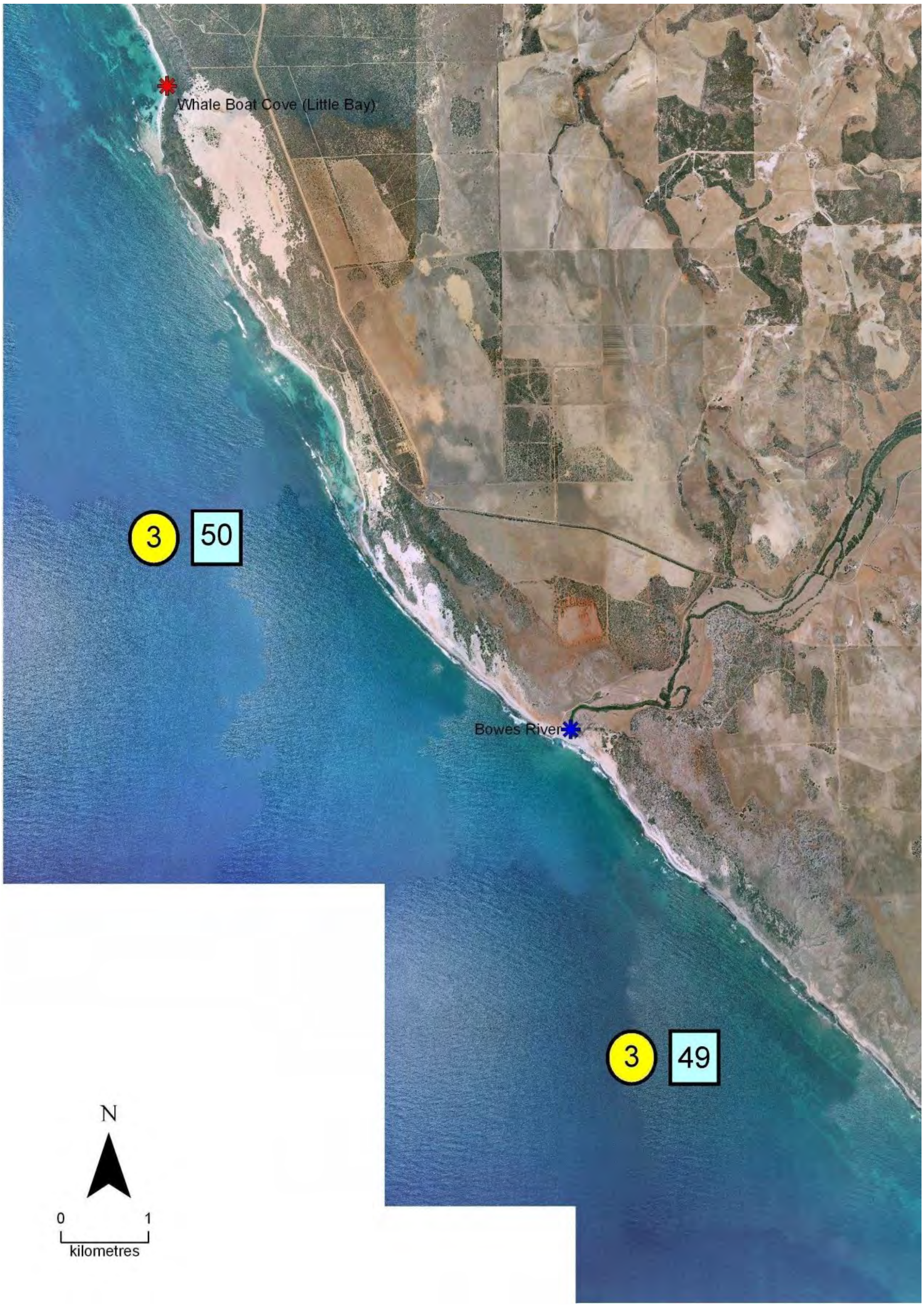

Figure C - 18: Vulnerability for Cells 49-50

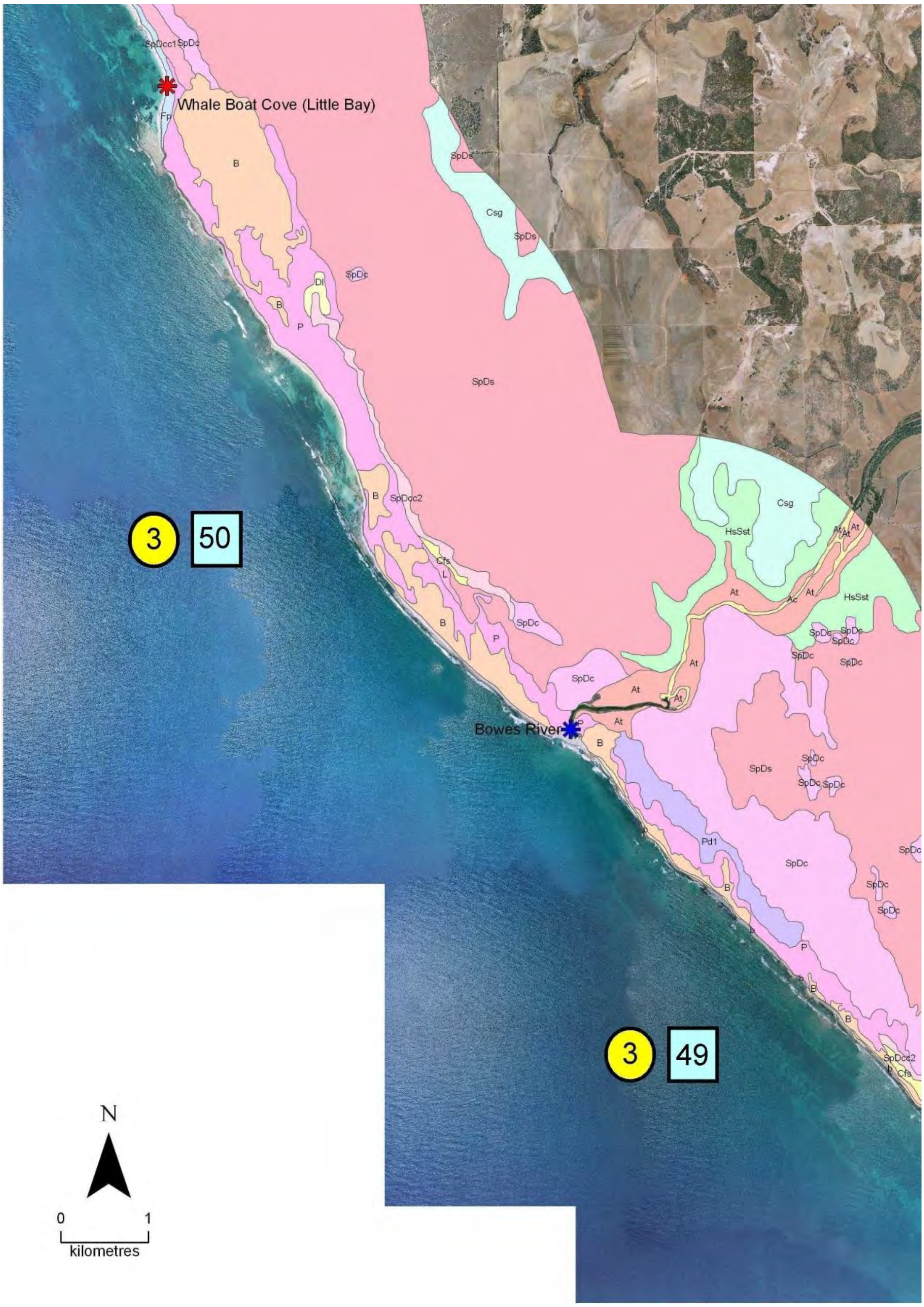

Figure C - 19: Landform for Cells 49-50

Figure C - 20: Vulnerability for Cell 49

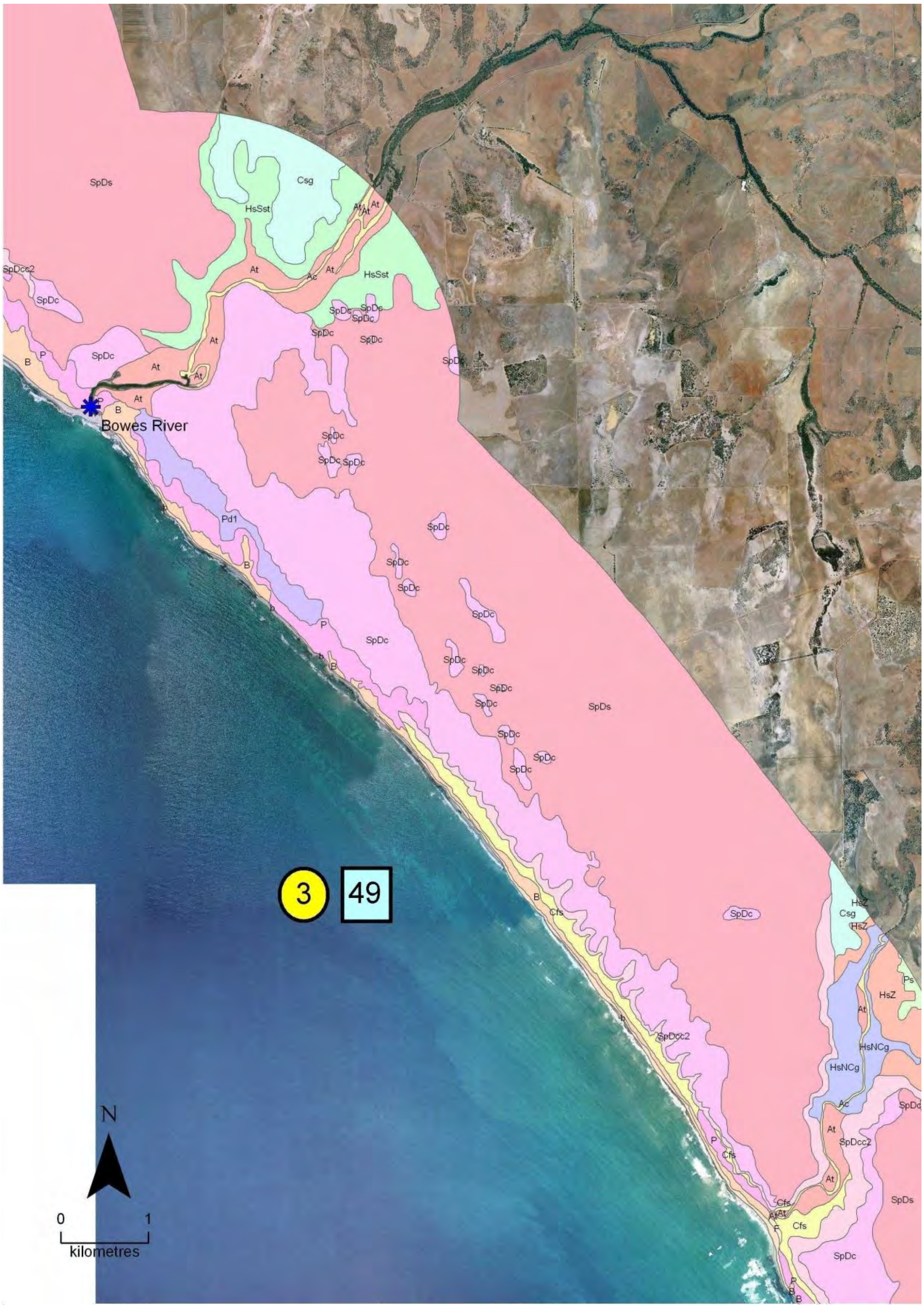

Figure C - 21: Landforms for Cell 49

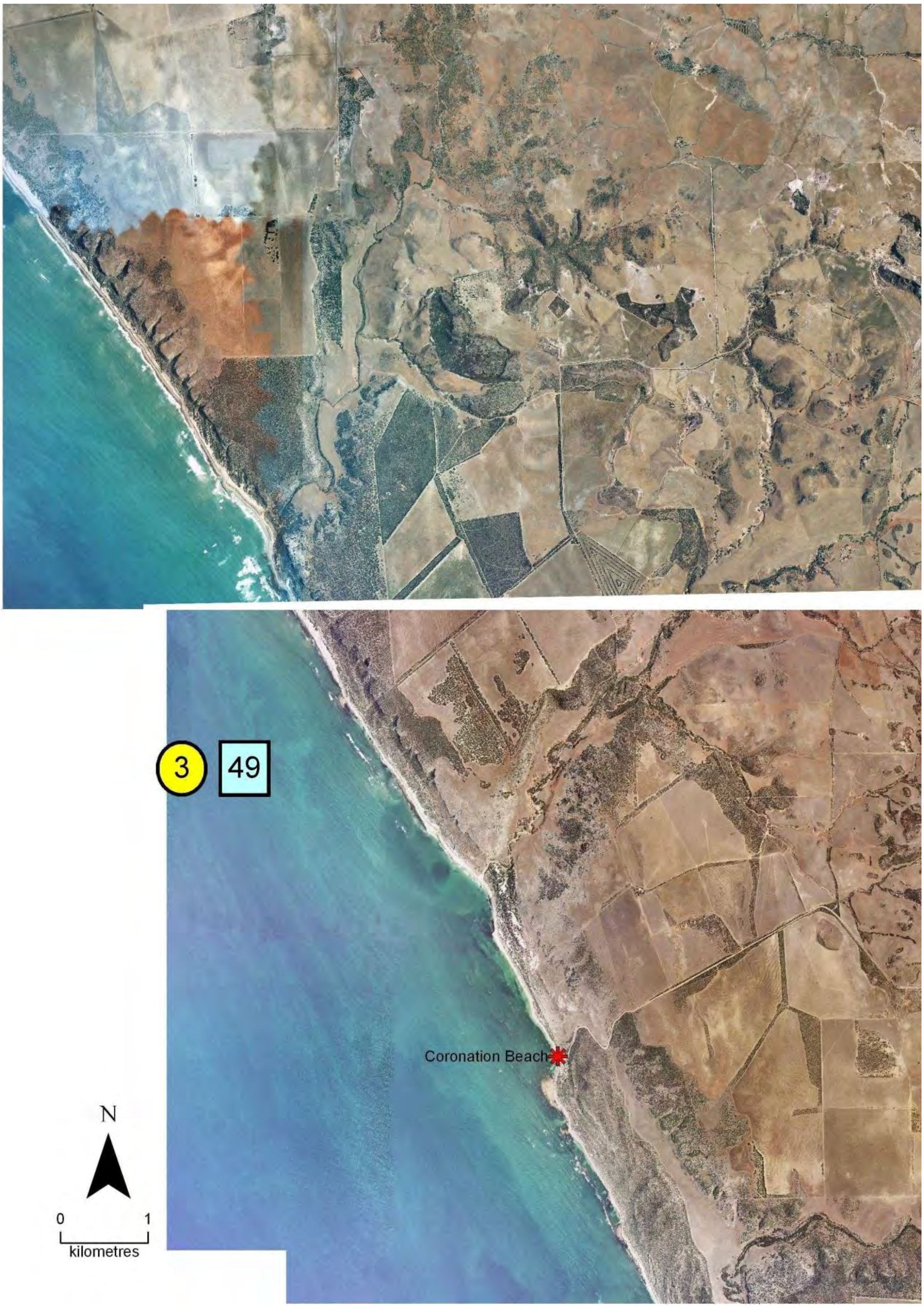

Figure C - 22: Vulnerability for Cell 49

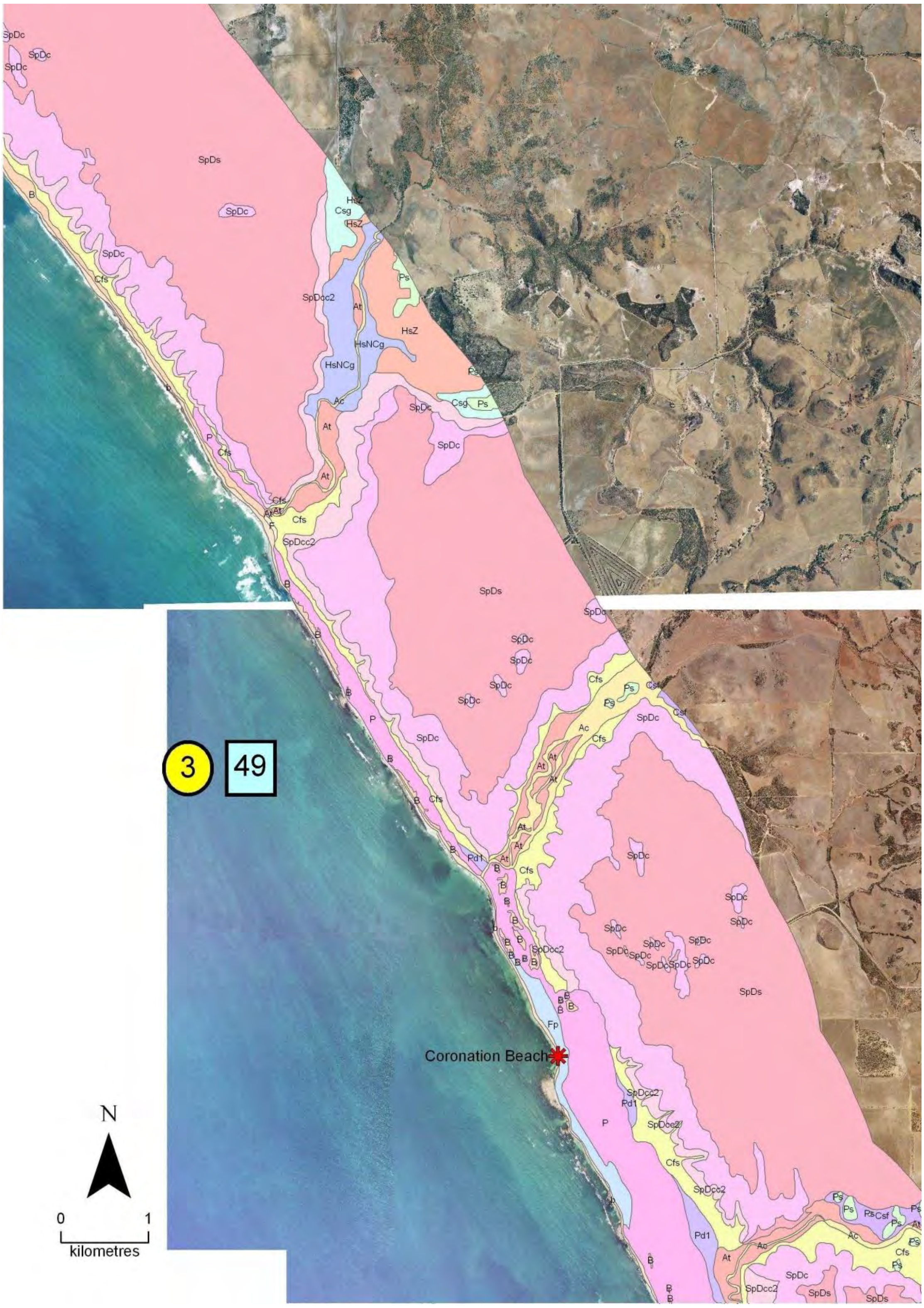

Figure C - 23: Landforms for Cell 49

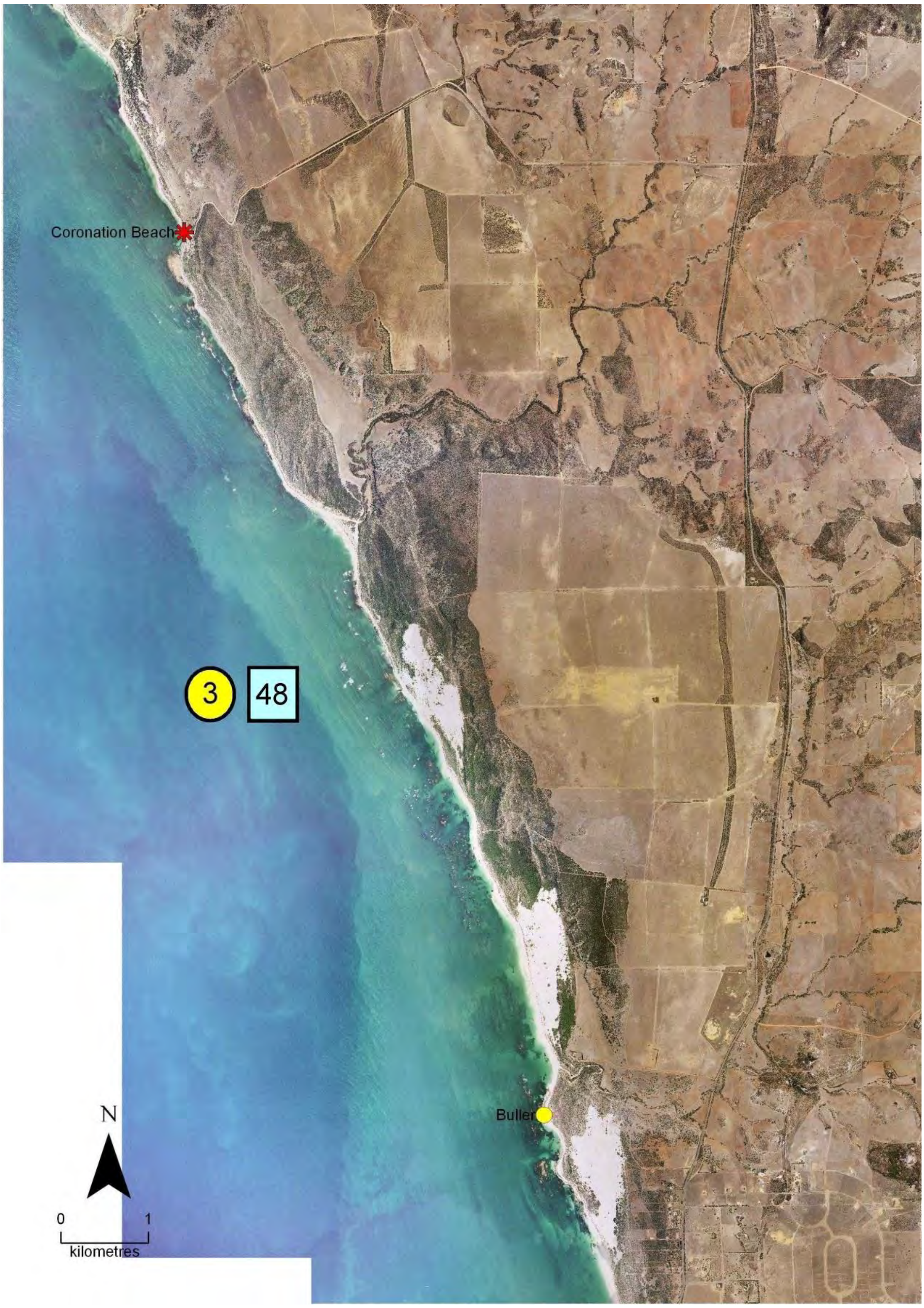

Figure C - 24: Vulnerability for Cell 48

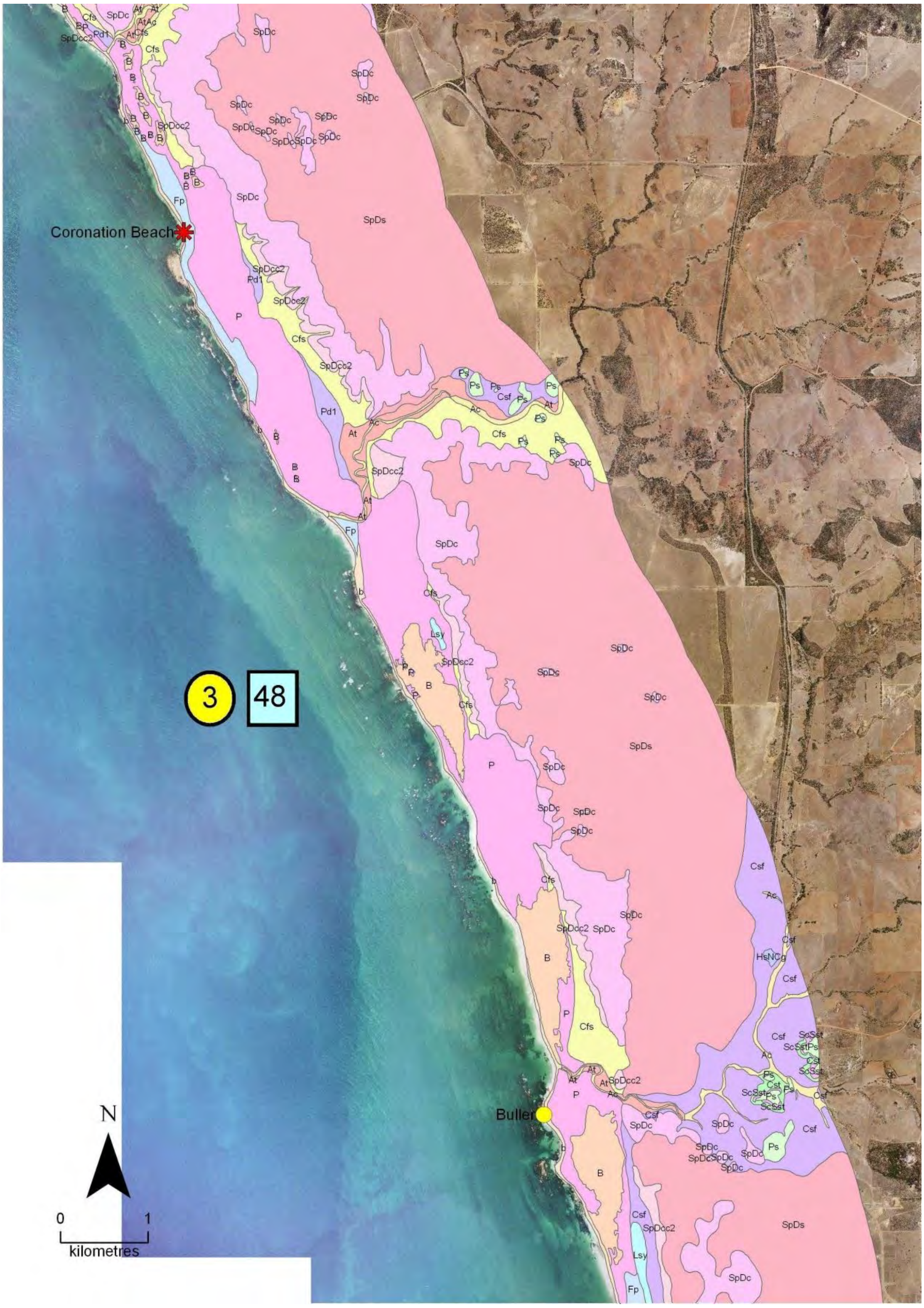

Figure C - 25: Landforms for Cell 48

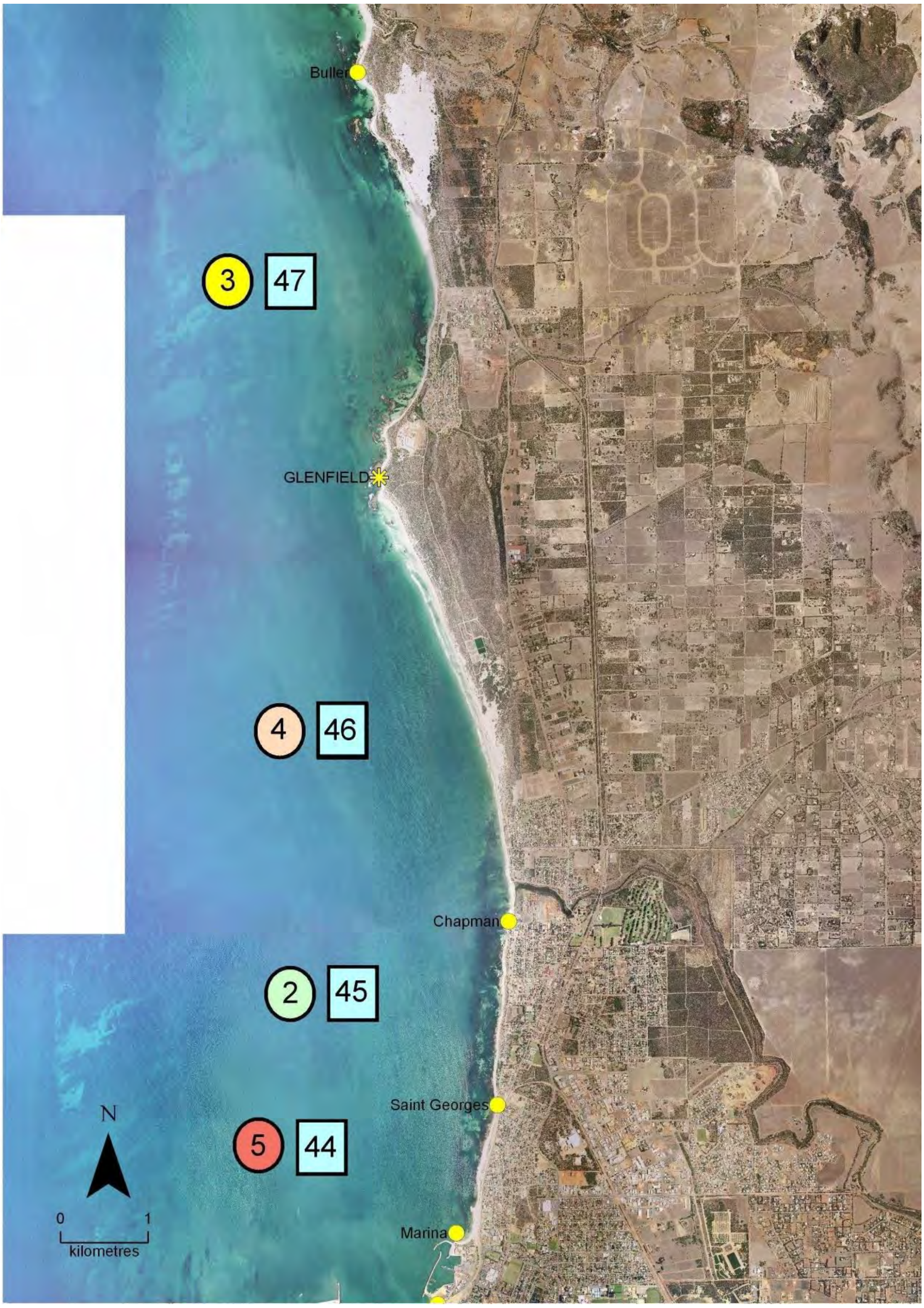

Figure C - 26: Vulnerability for Cells 44-47

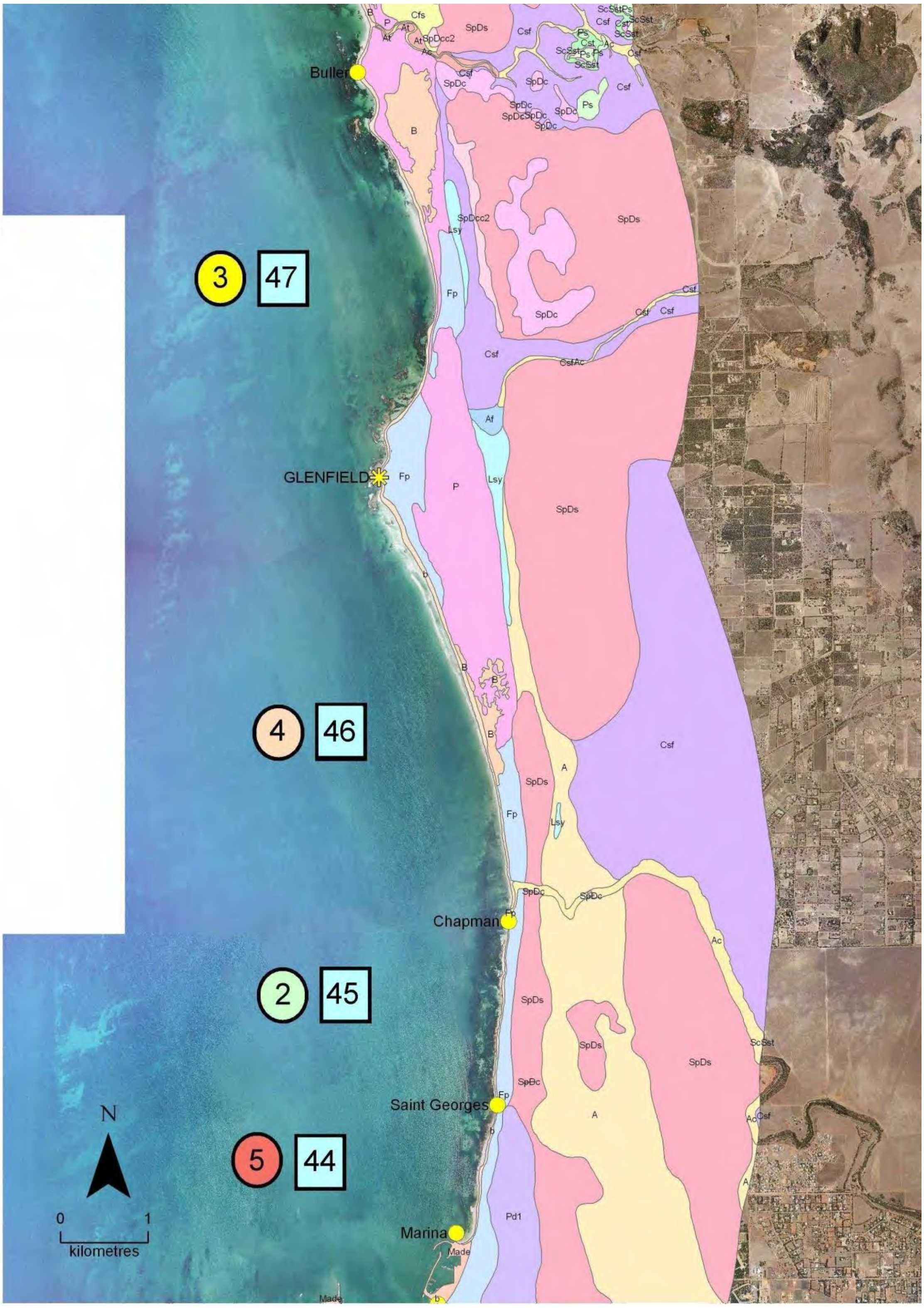

Figure C - 27: Landforms for Cells 44-47

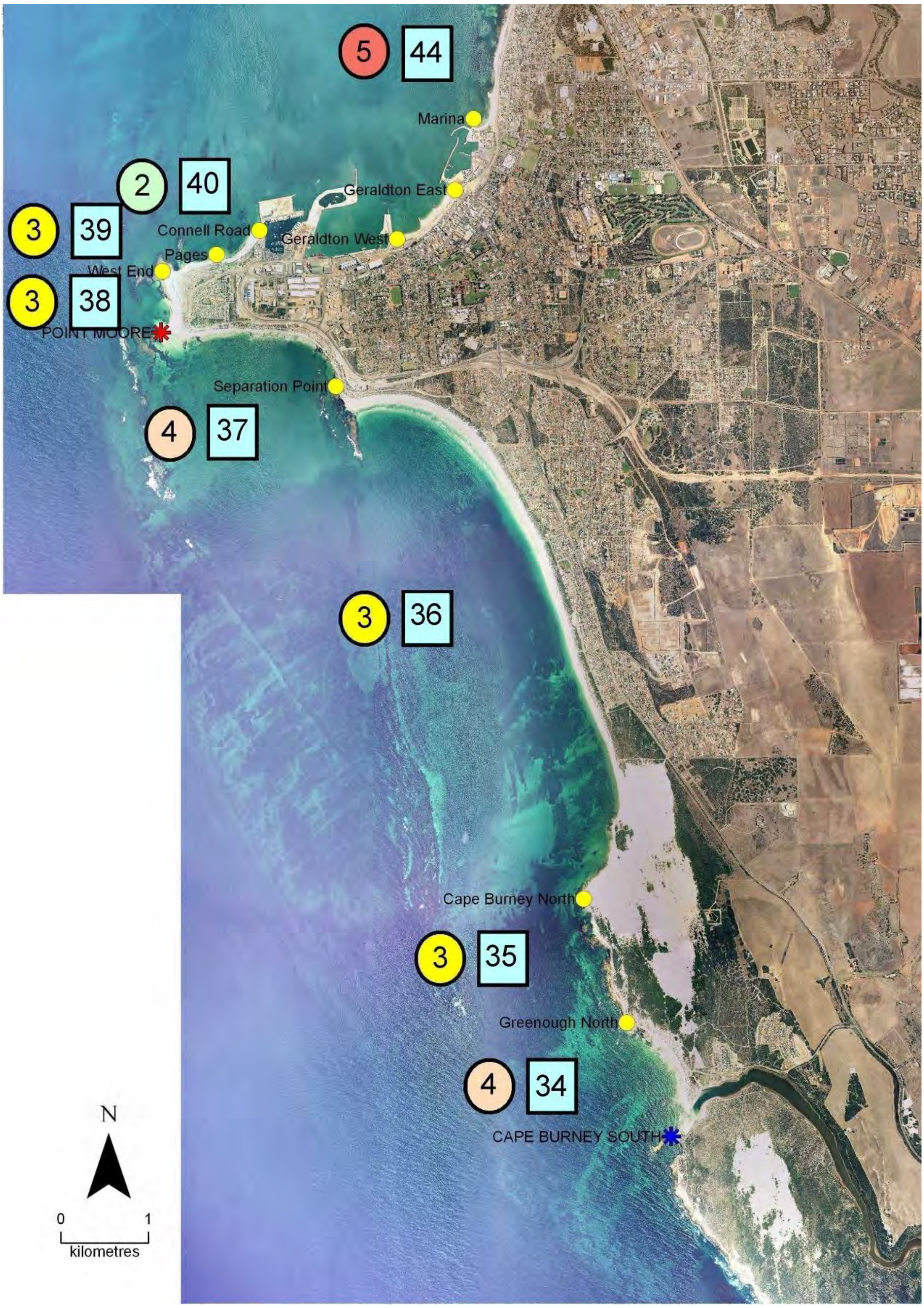

Figure C - 28: Vulnerability for Cells 34-44

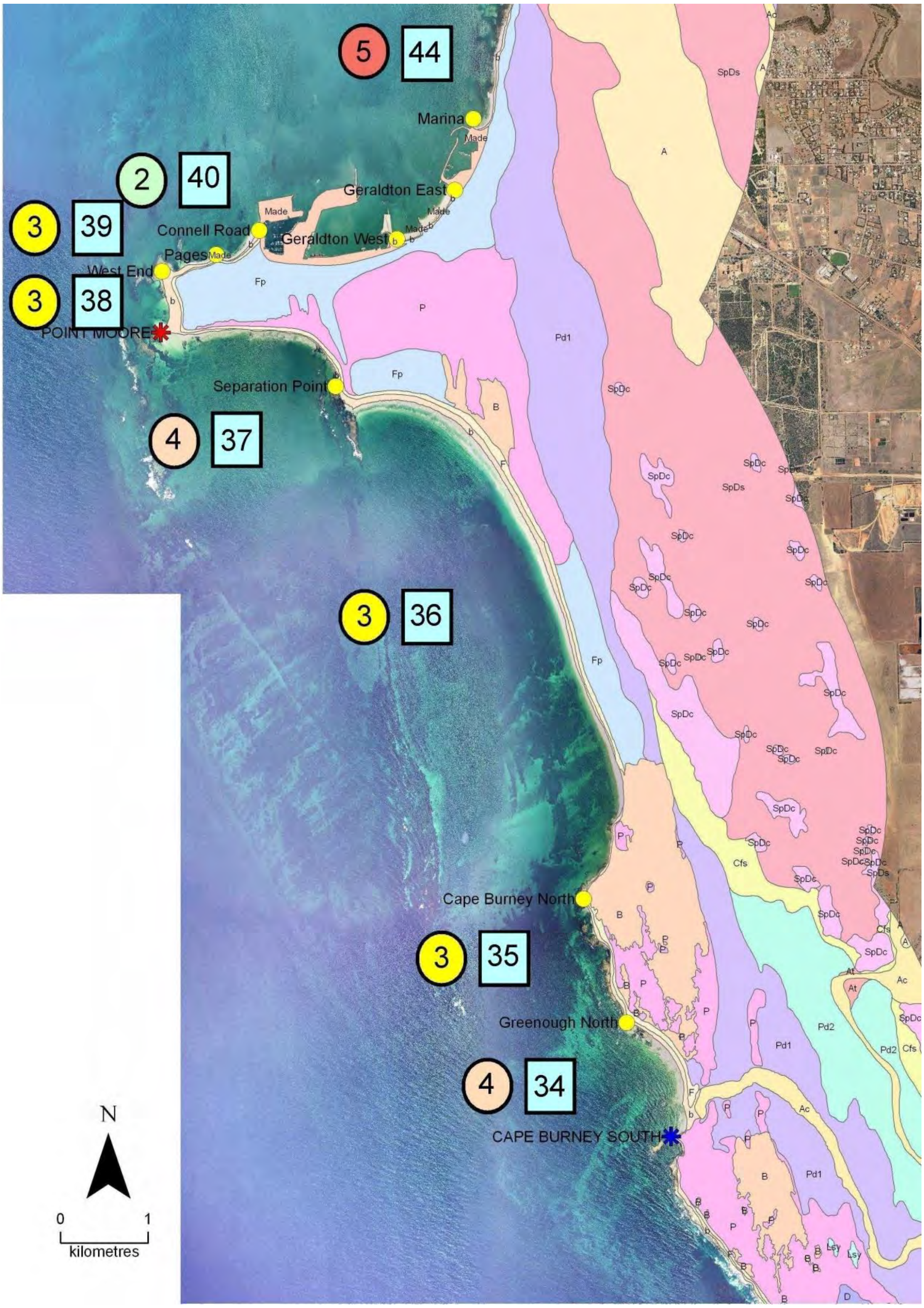

Figure C - 29: Landforms for Cells 34-44

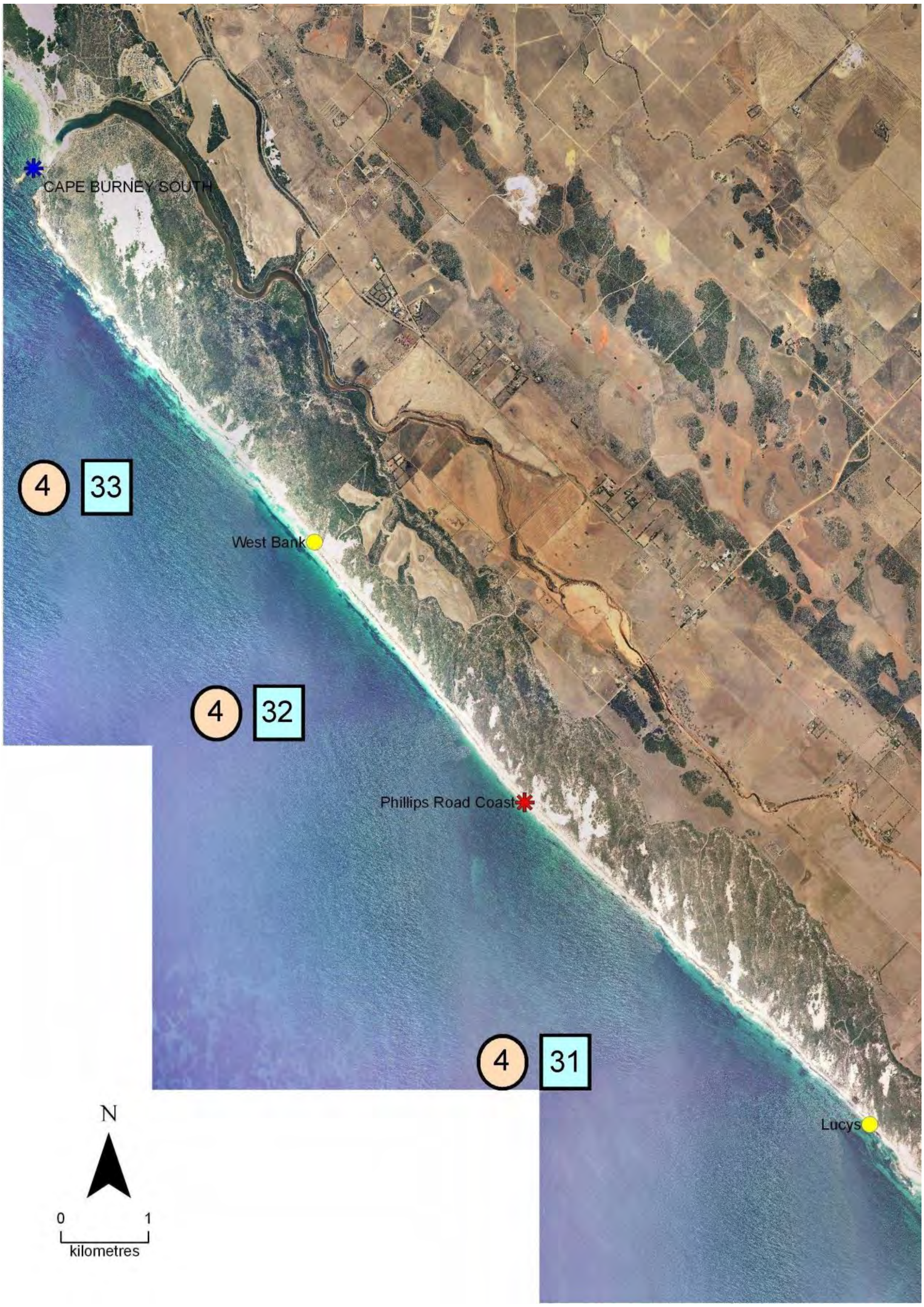

Figure C - 30: Vulnerability for Cells 31-33

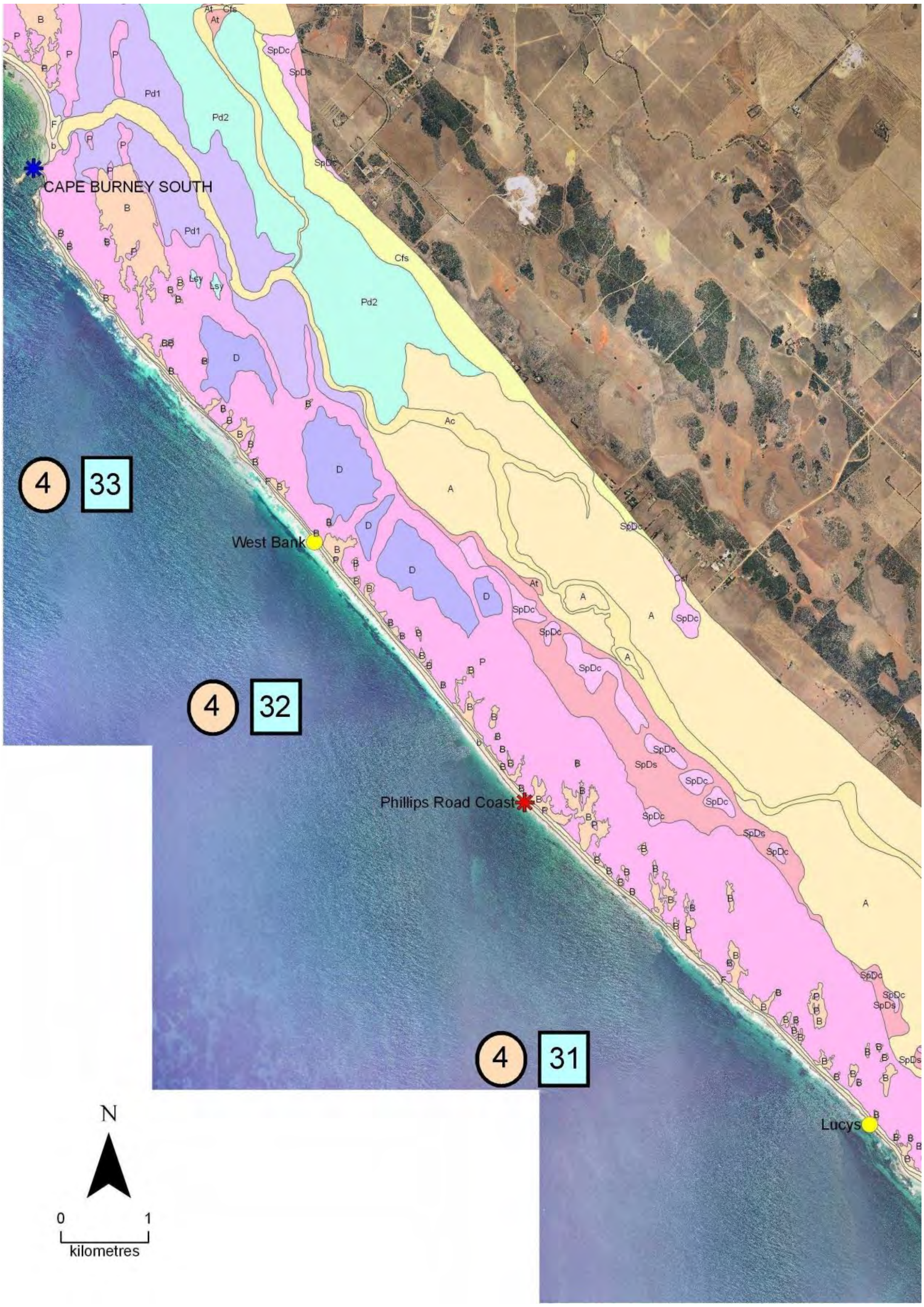

Figure C - 31: Landforms for Cells 31-33

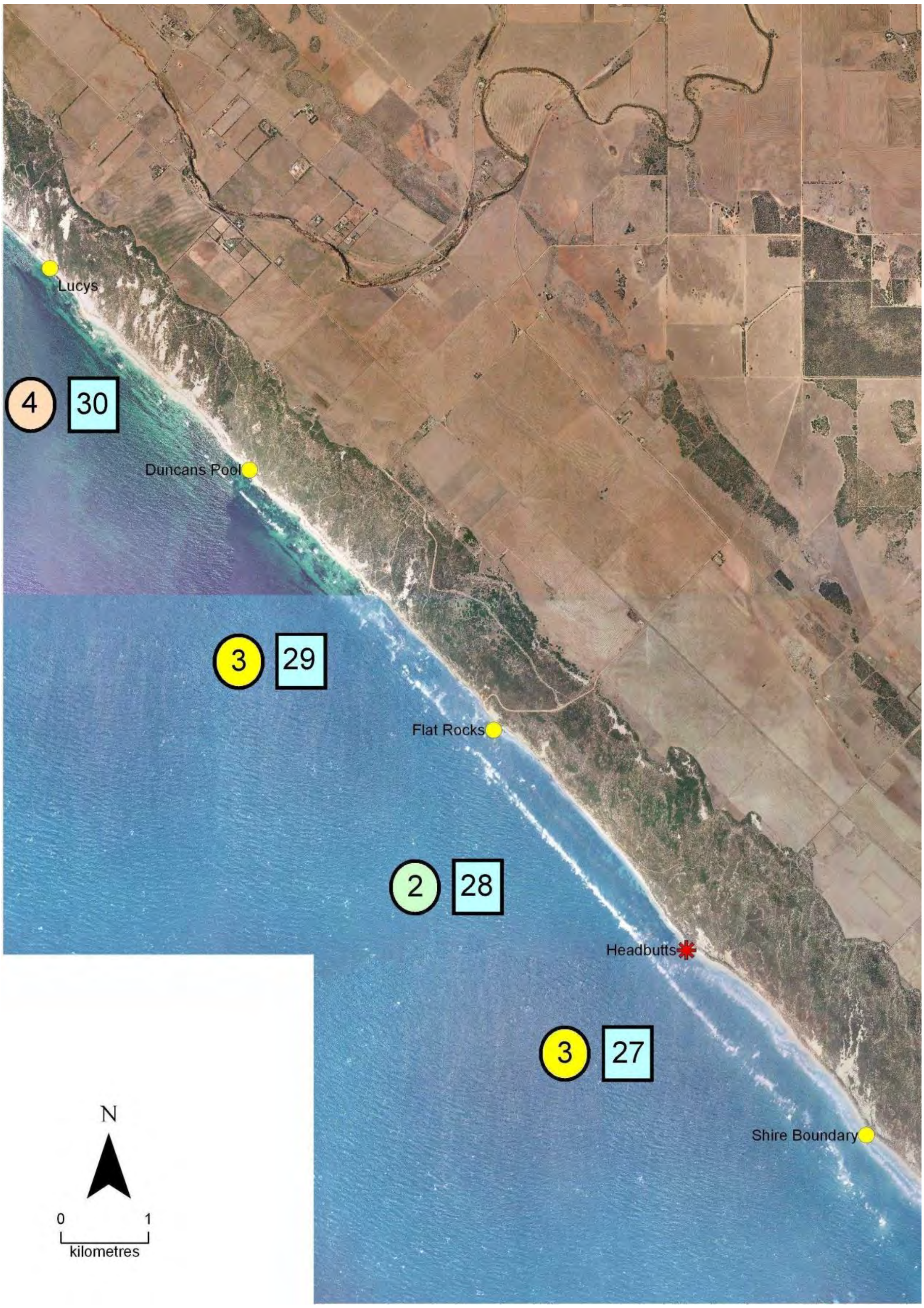

Figure C - 32: Vulnerability for Cells 27-30

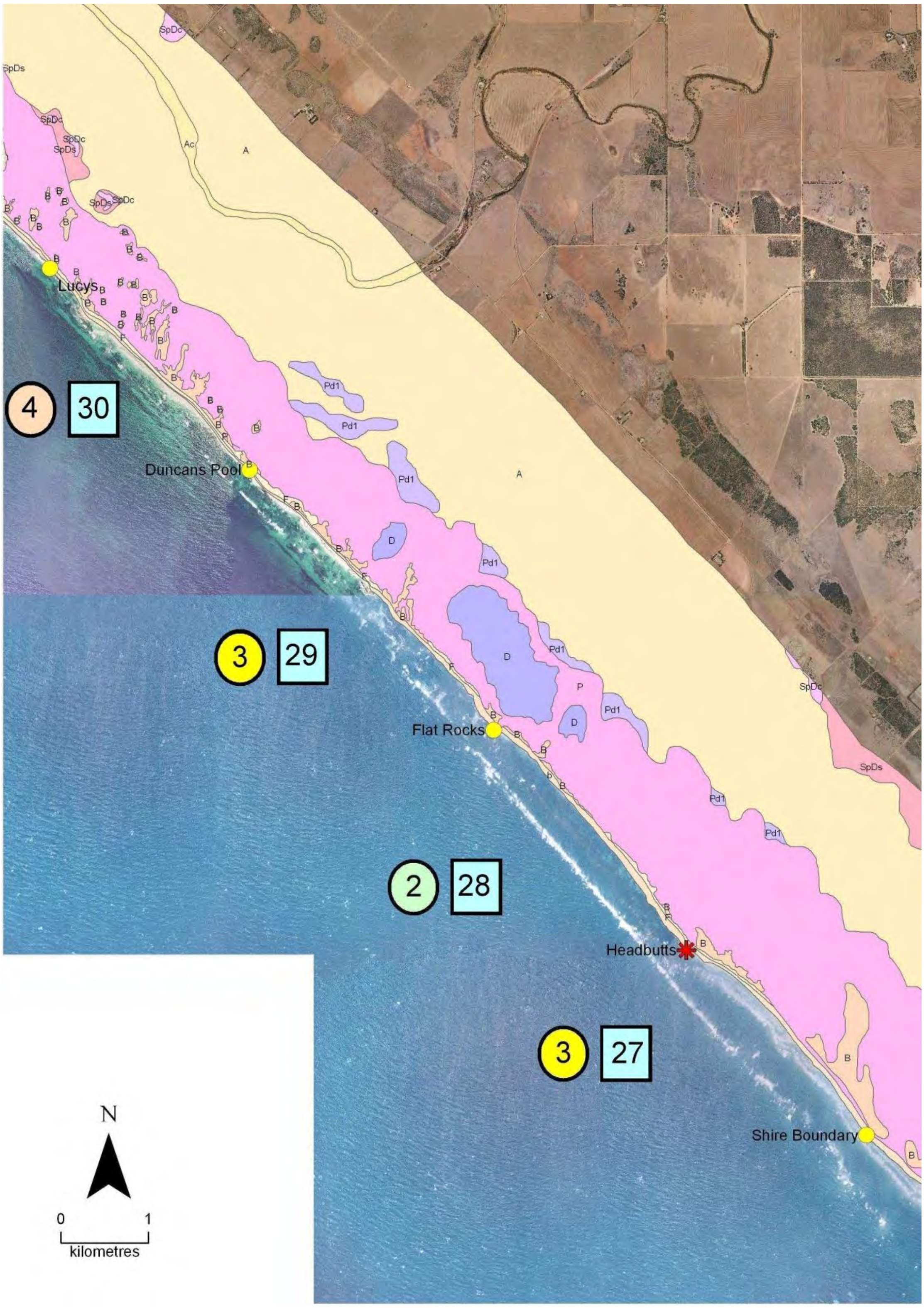

Figure C - 33: Landforms for Cells 27-30

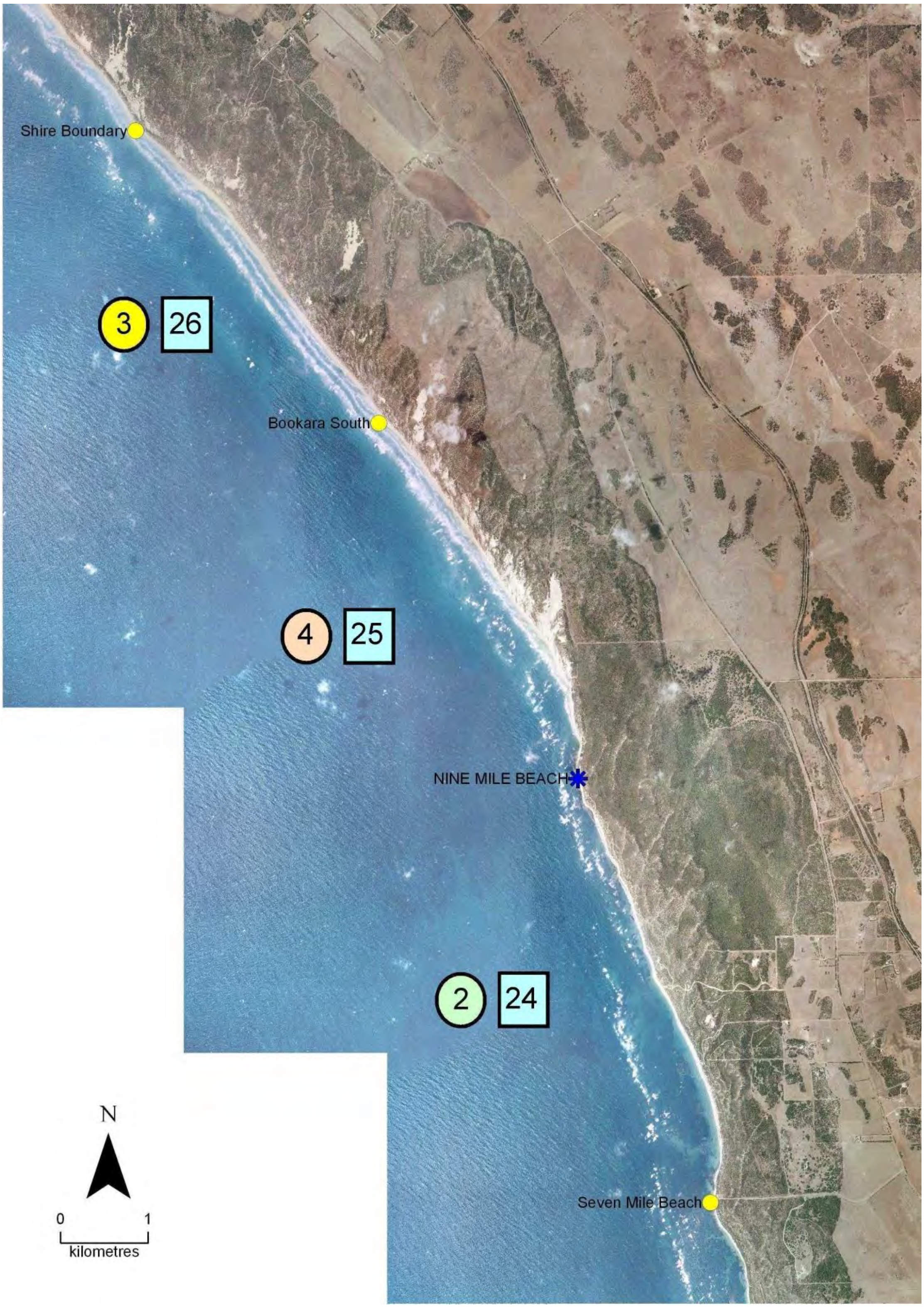

Figure C - 34: Vulnerability for Cells 24-26

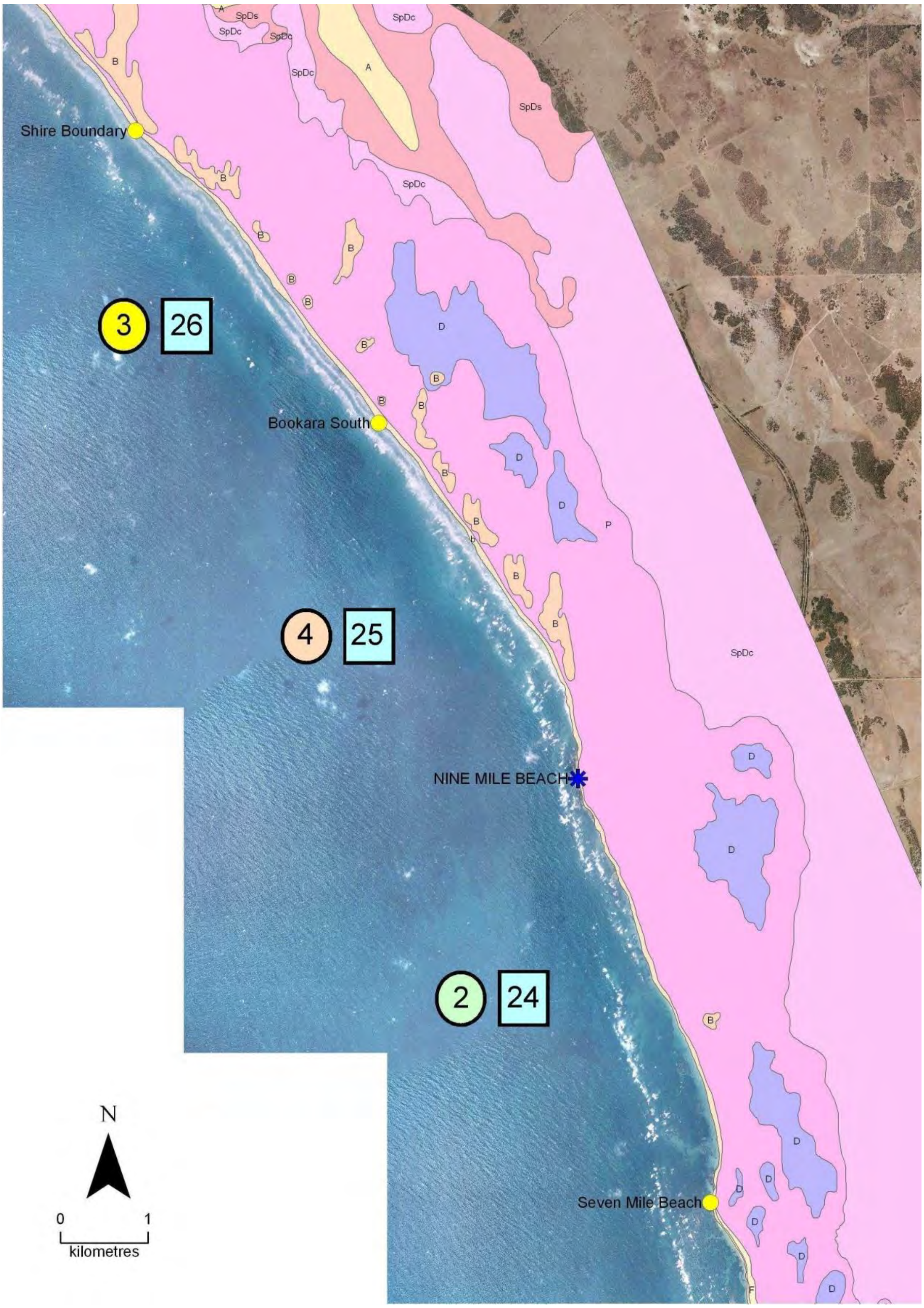

Figure C - 35: Landforms for Cells 24-26

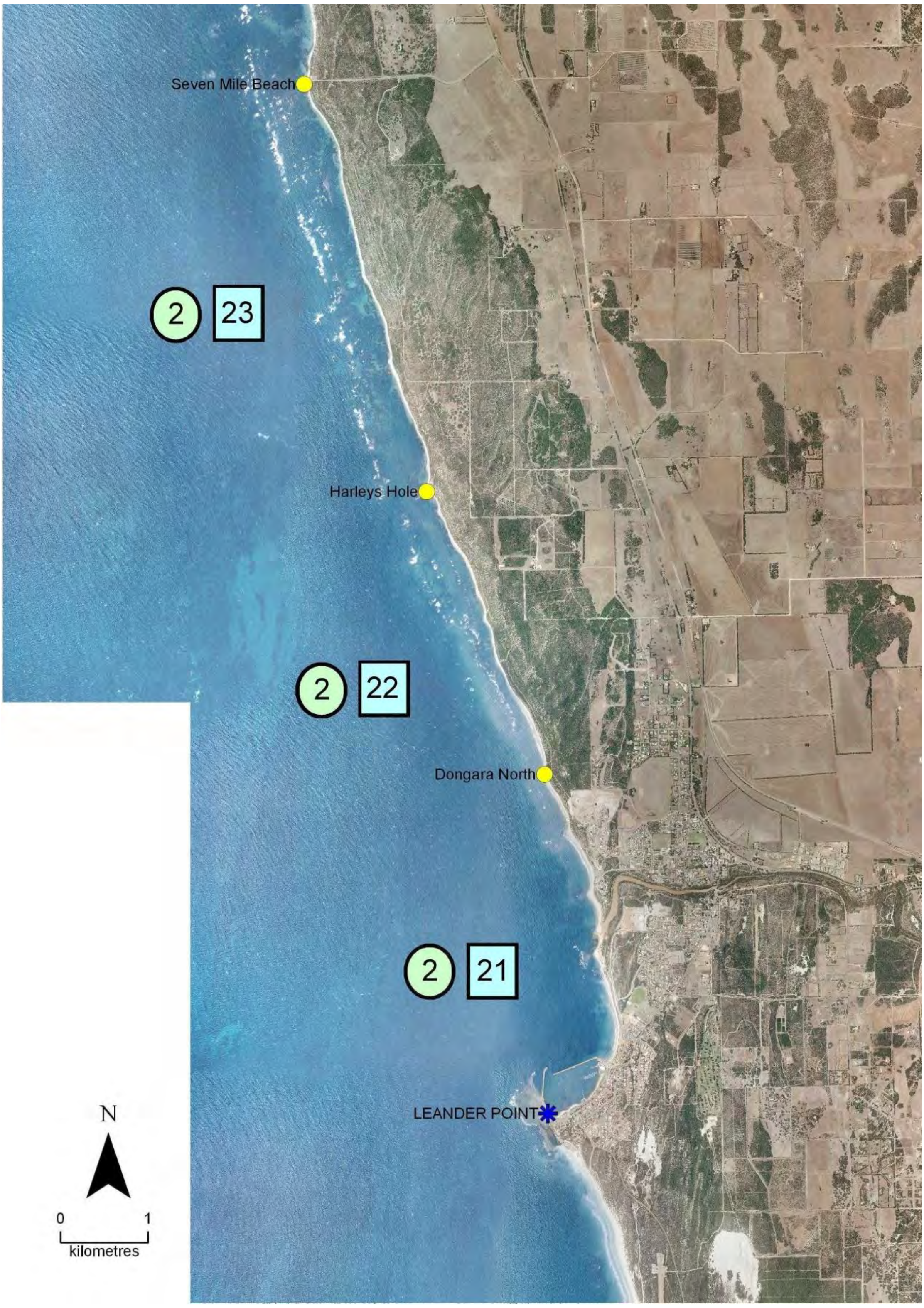

Figure C - 36: Vulnerability for Cells 21-23

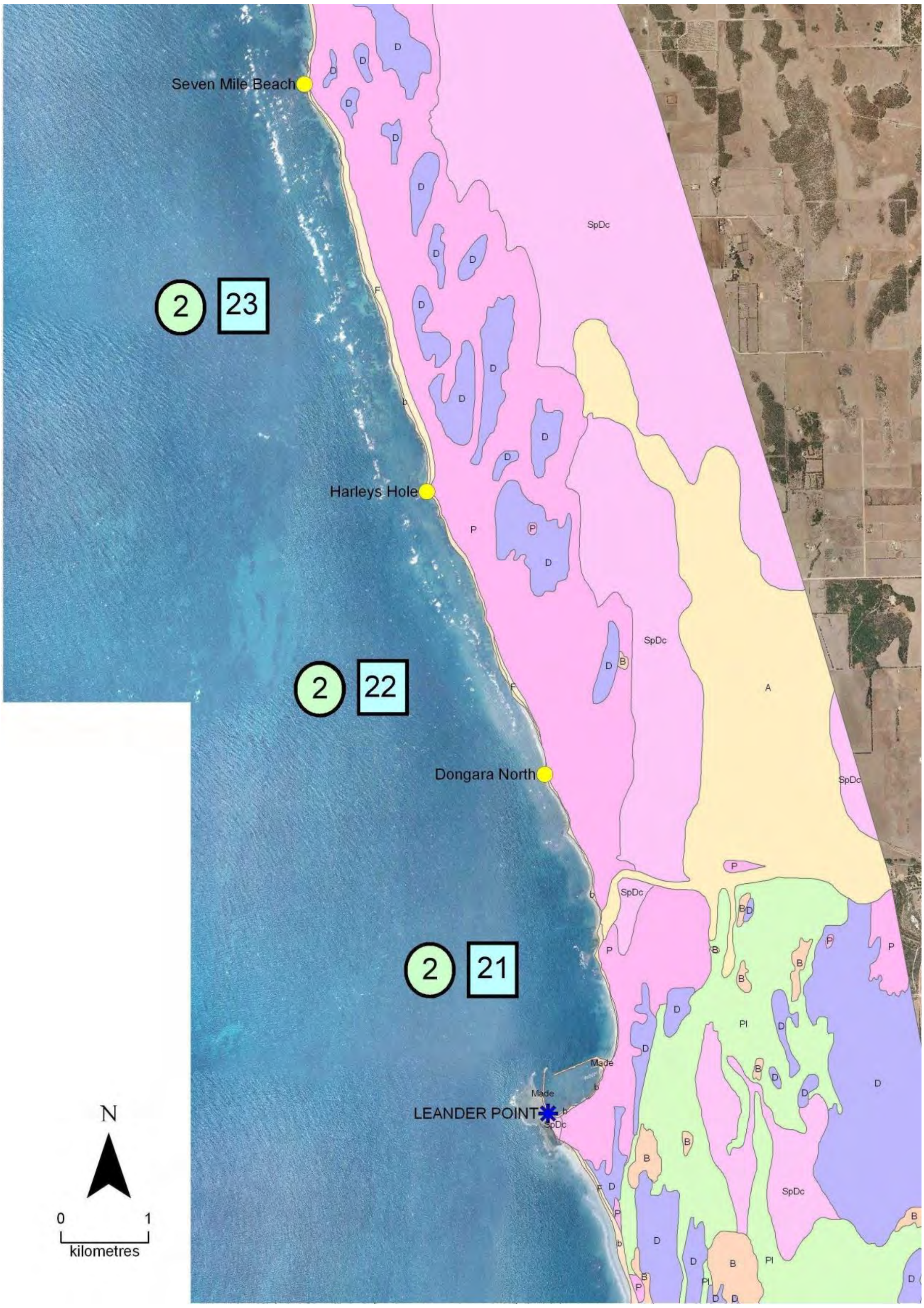

Figure C - 37: Landforms for Cells 21-23

Figure C - 38: Vulnerability for Cells 19-20

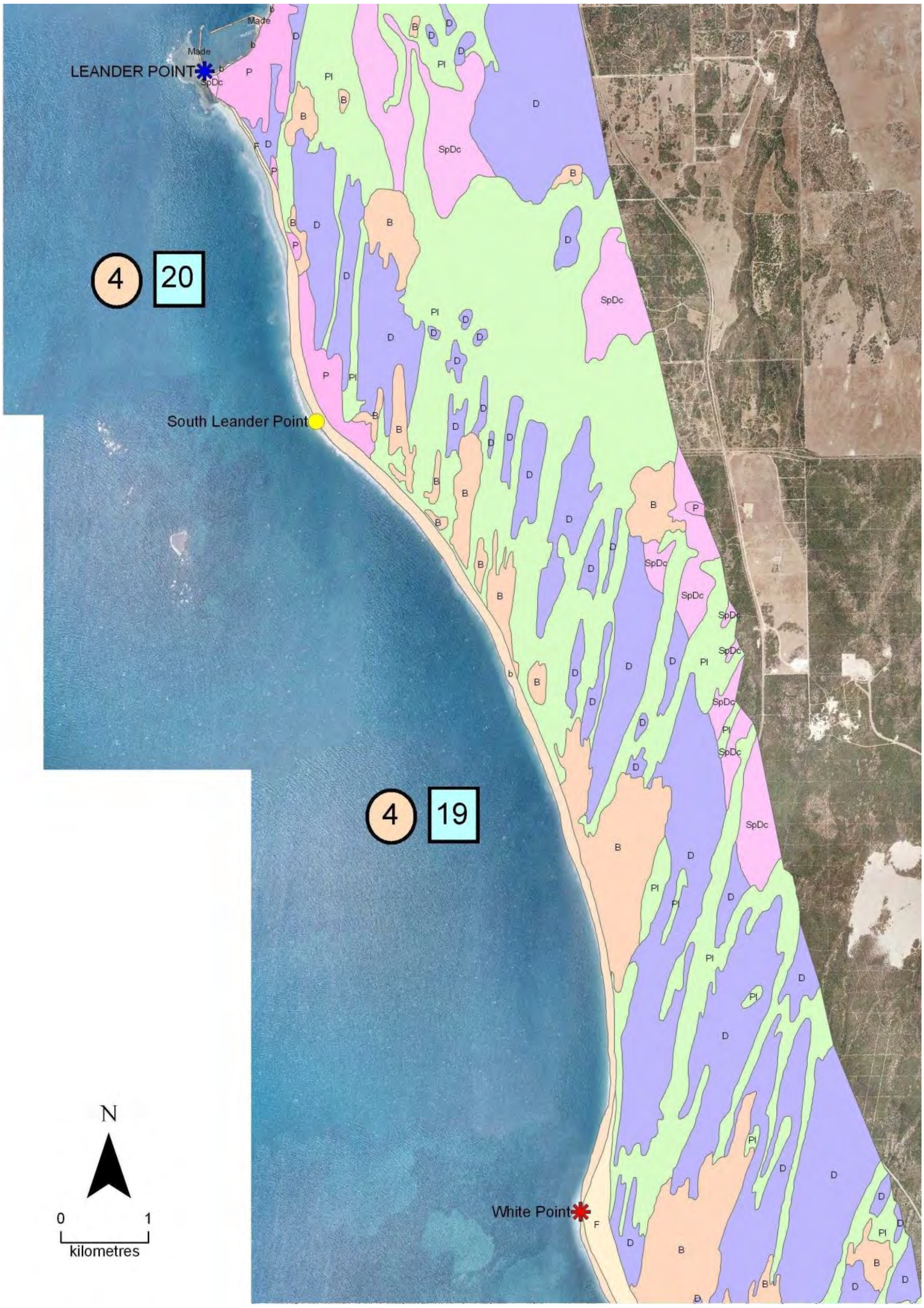

Figure C - 39: Landforms for Cells 19-20

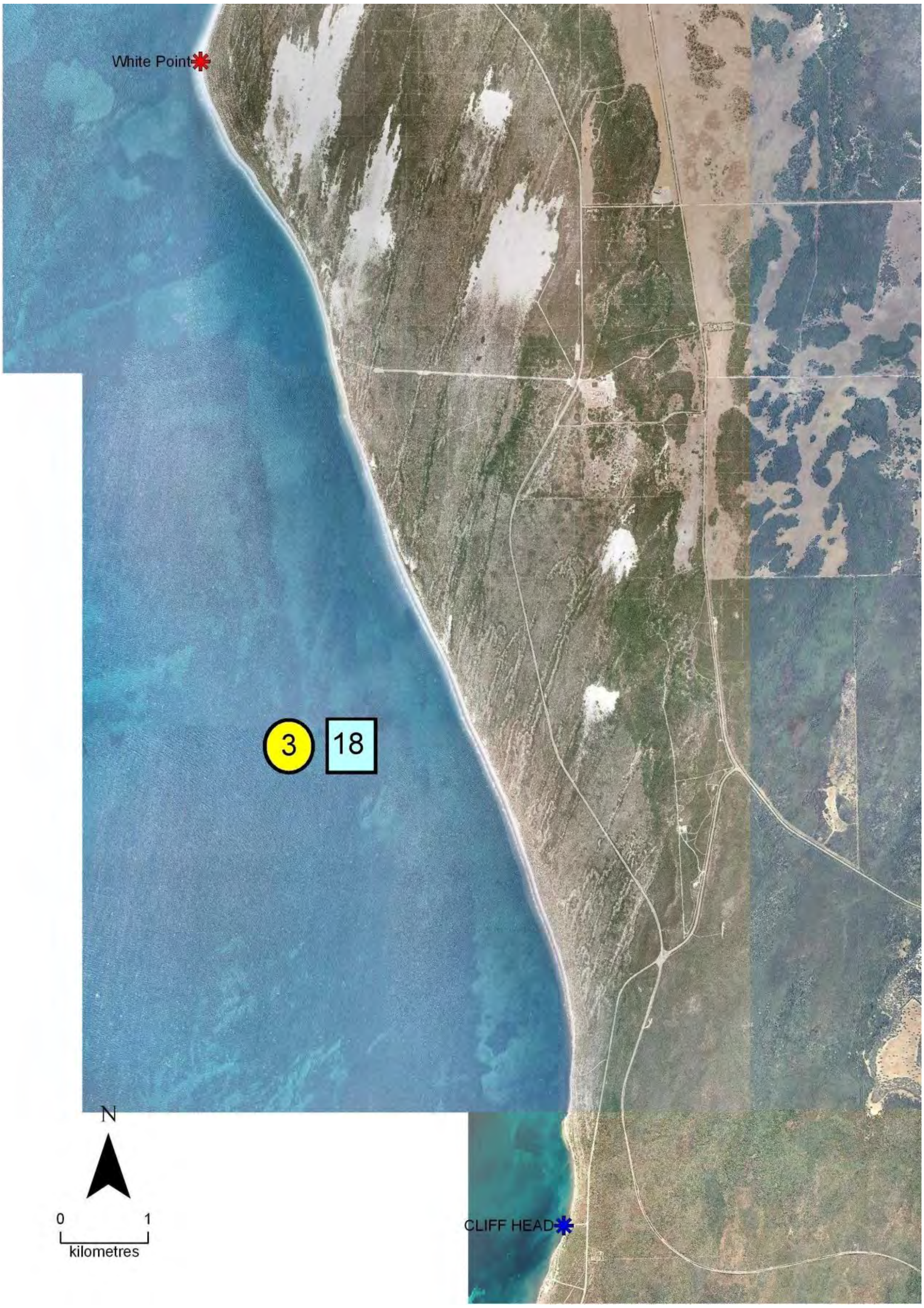

Figure C - 40: Vulnerability for Cell 18

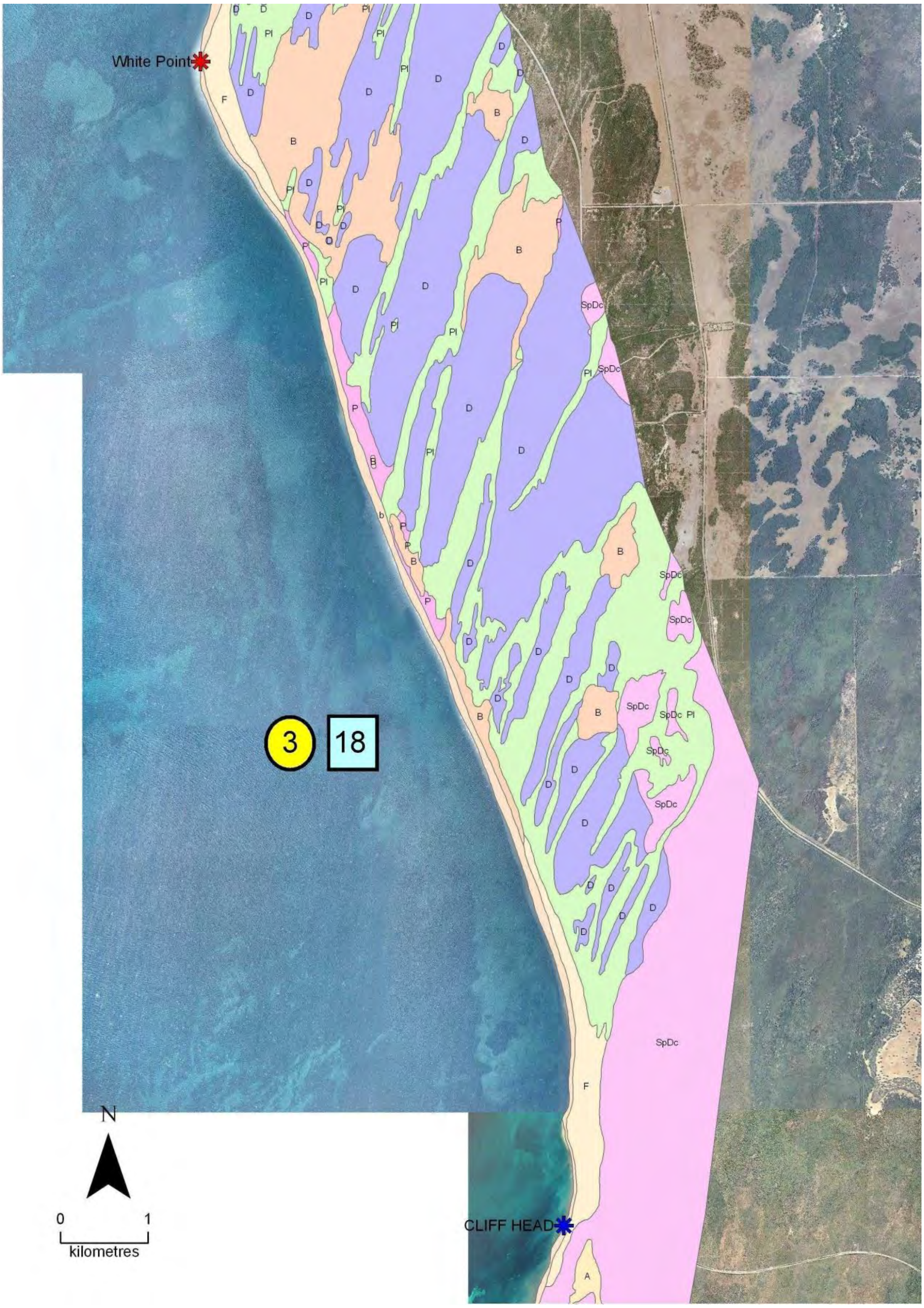

Figure C - 41: Landforms for Cell 18

Figure C - 42: Vulnerability for Cell 17

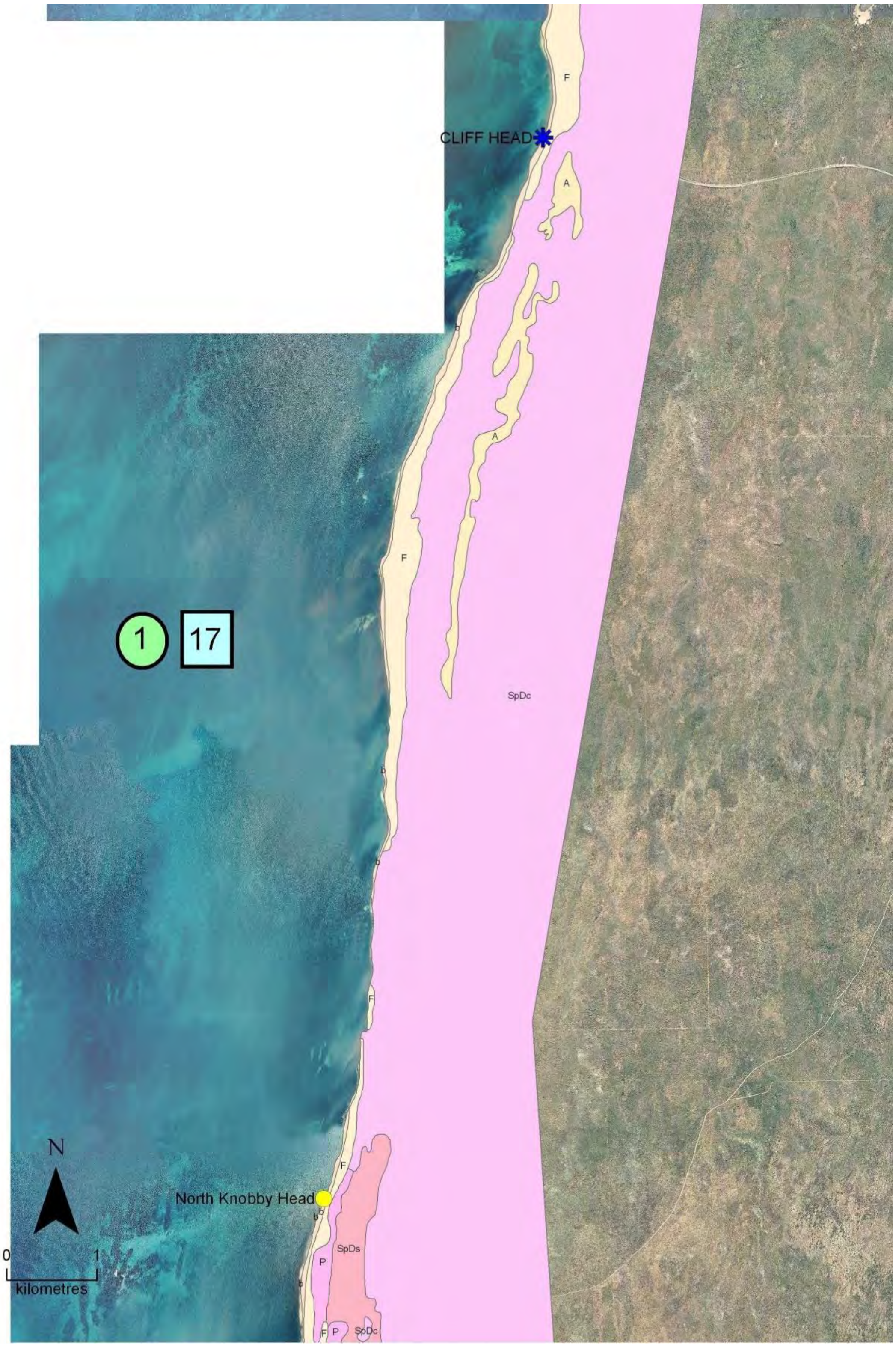

Figure C - 43: Landforms for Cell 17

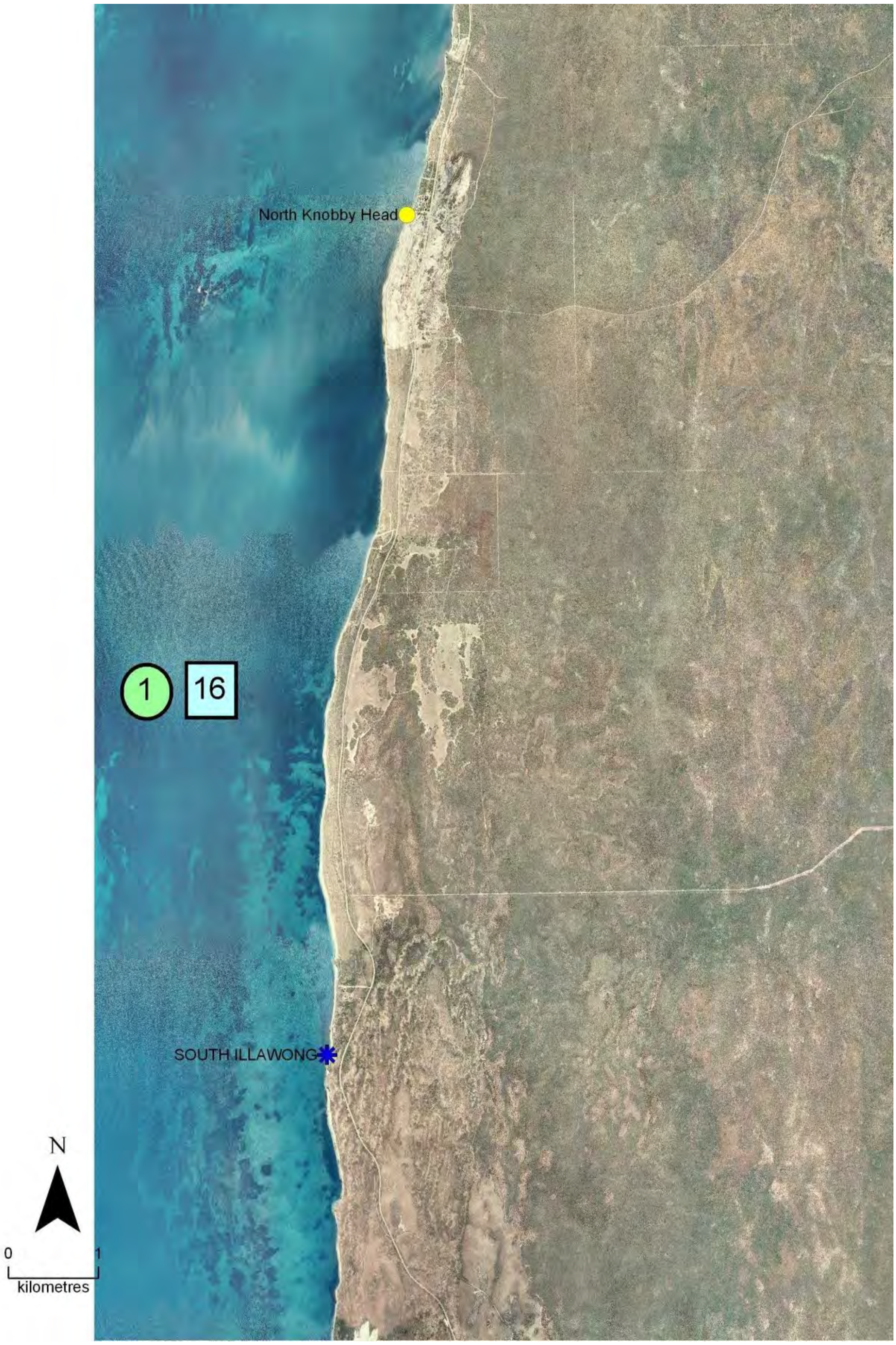

Figure C - 44: Vulnerability for Cell 16

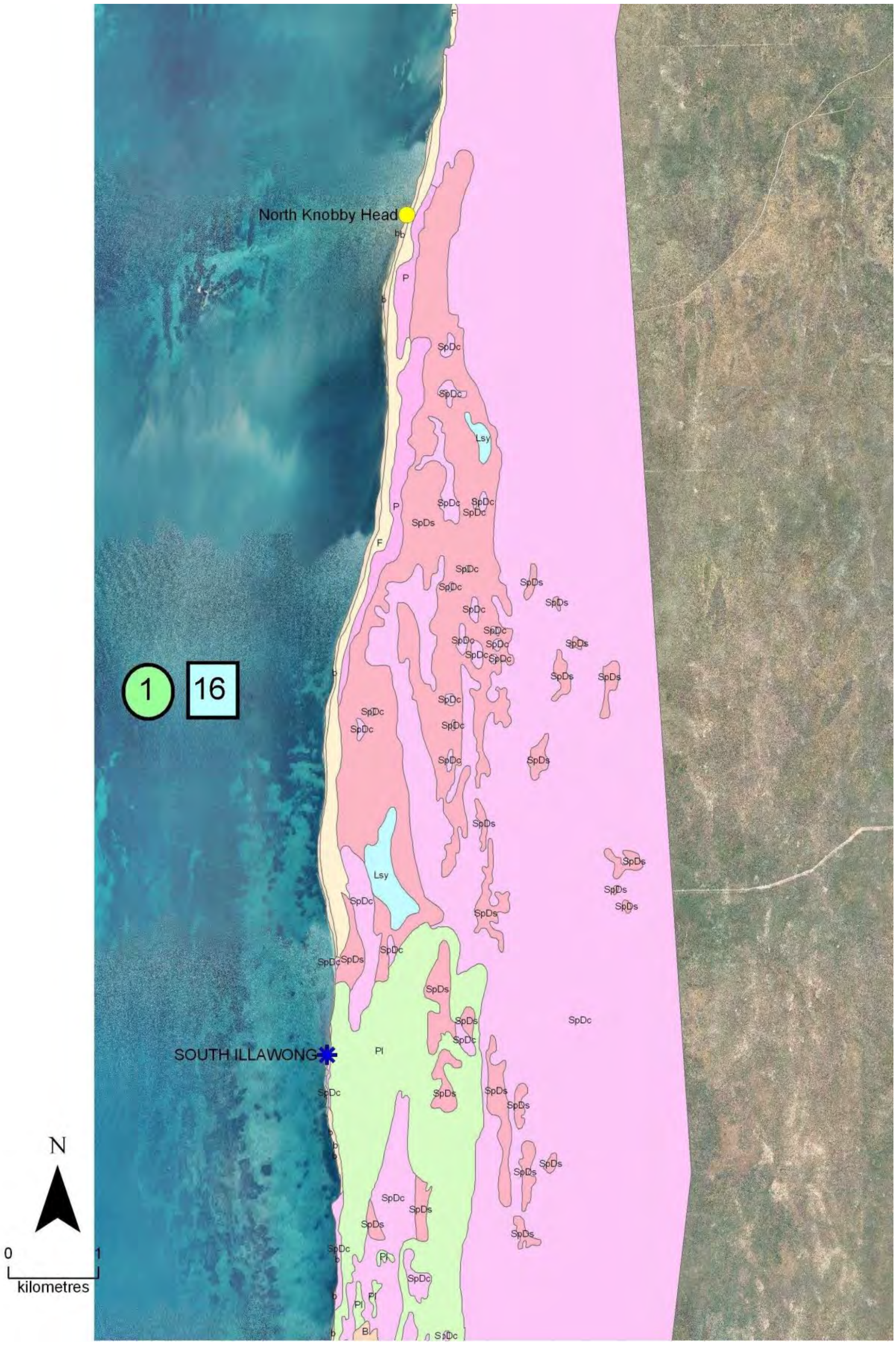

Figure C - 45: Landforms for Cell 16

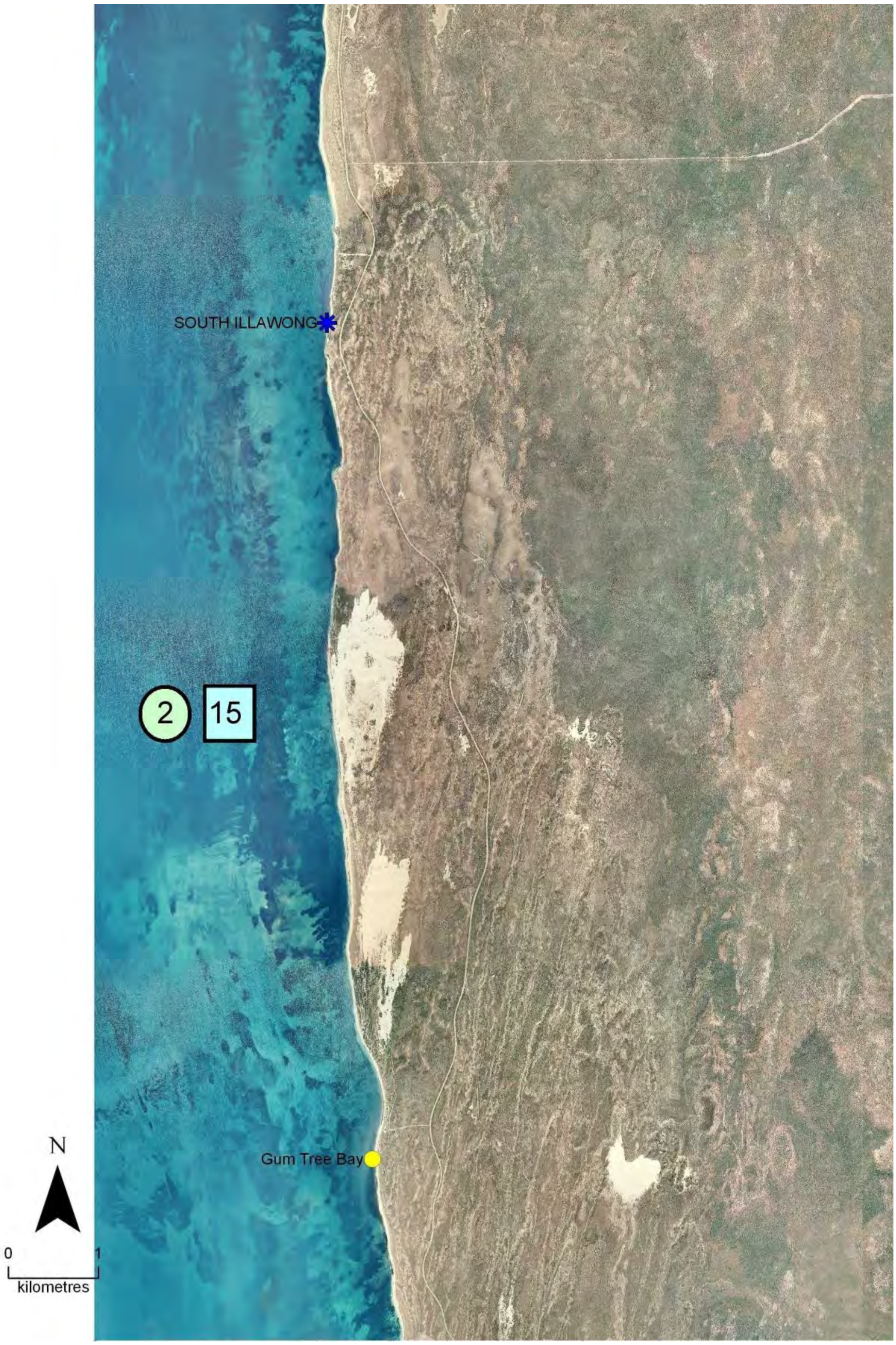

Figure C - 46: Vulnerability for Cell 15

Figure C - 47: Landforms for Cell 15

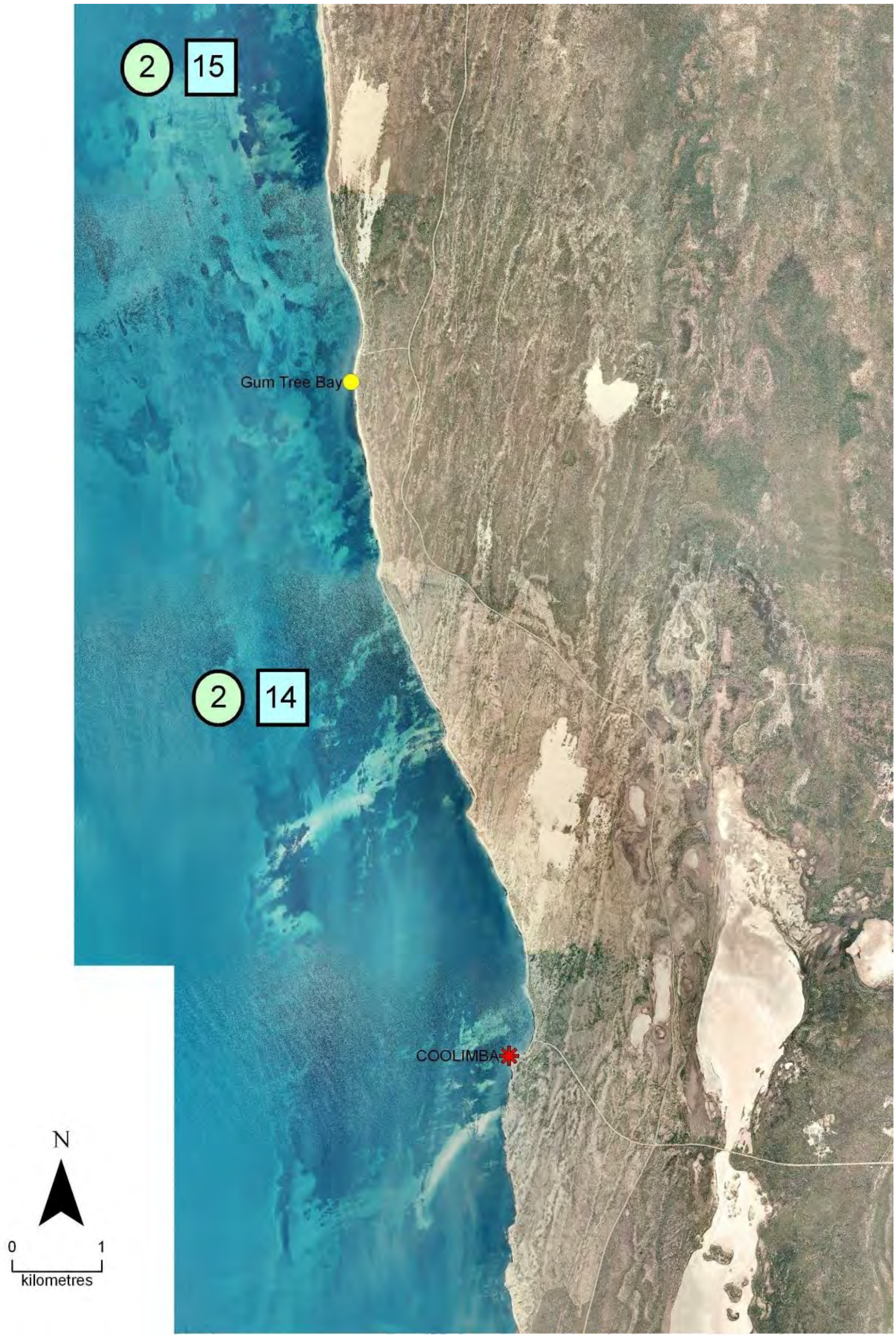

Figure C - 48: Vulnerability for Cells 14-15

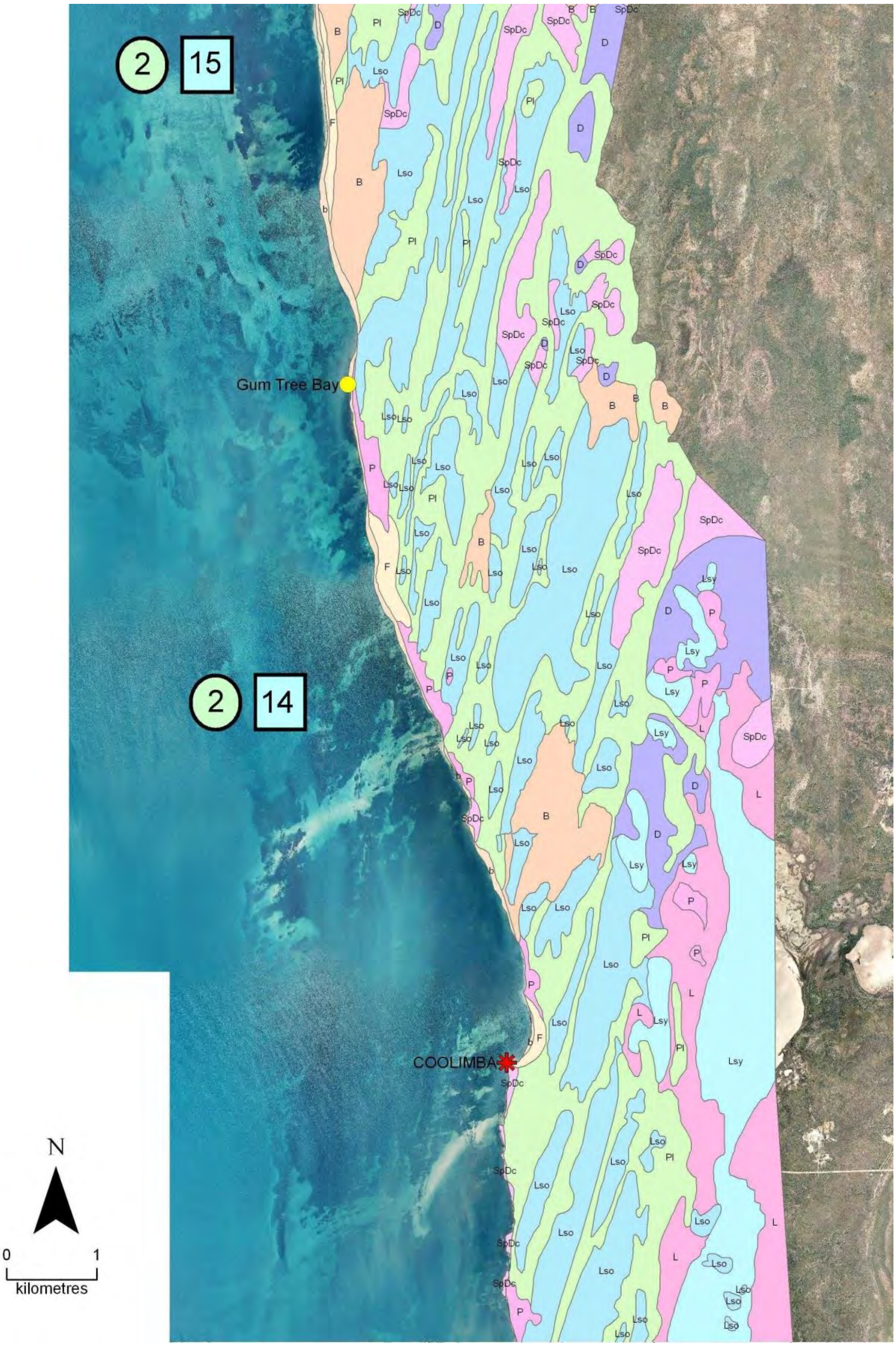

Figure C - 49: Landforms for Cells 14-15

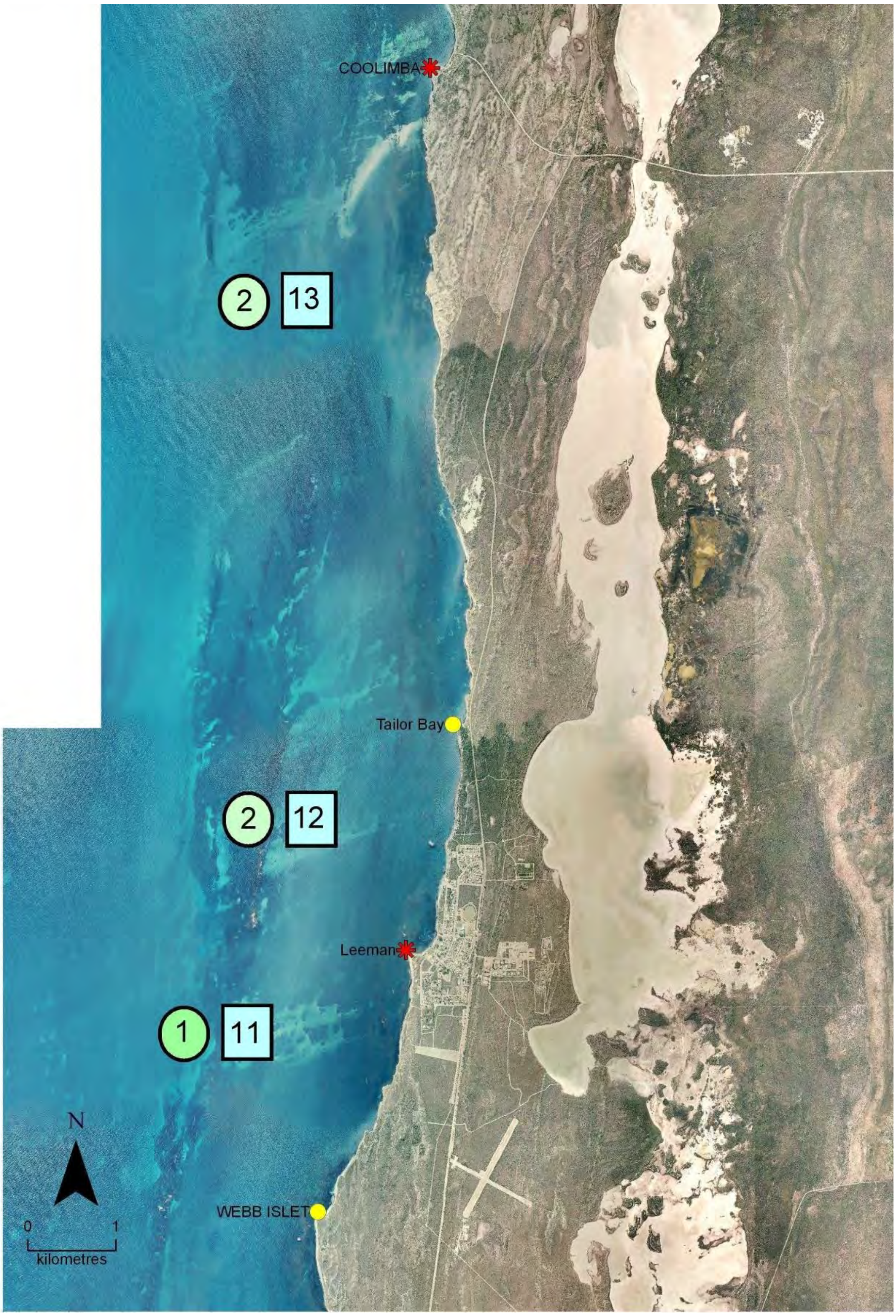

Figure C - 50: Vulnerability for Cells 11-13

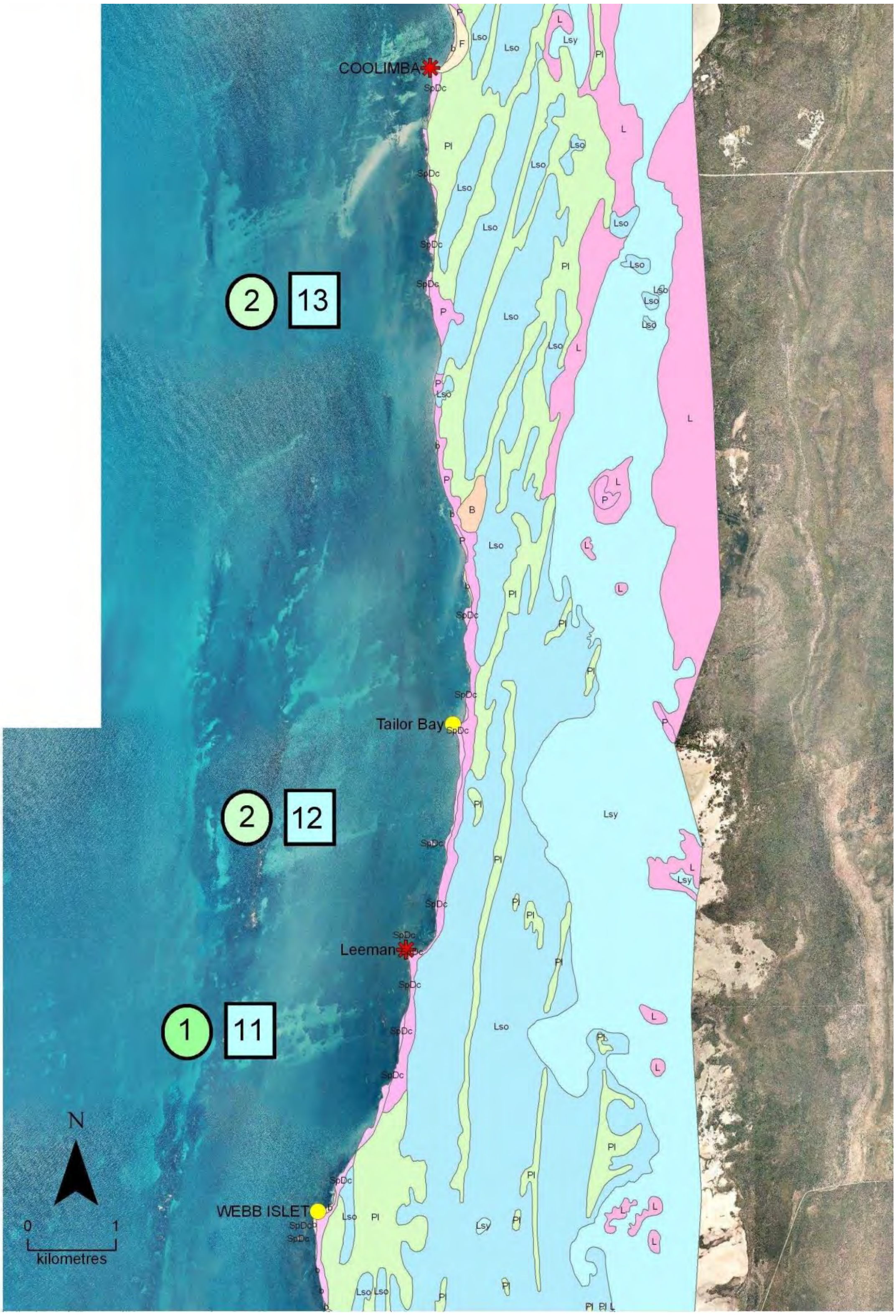

Figure C - 51: Landforms for Cells 11-13

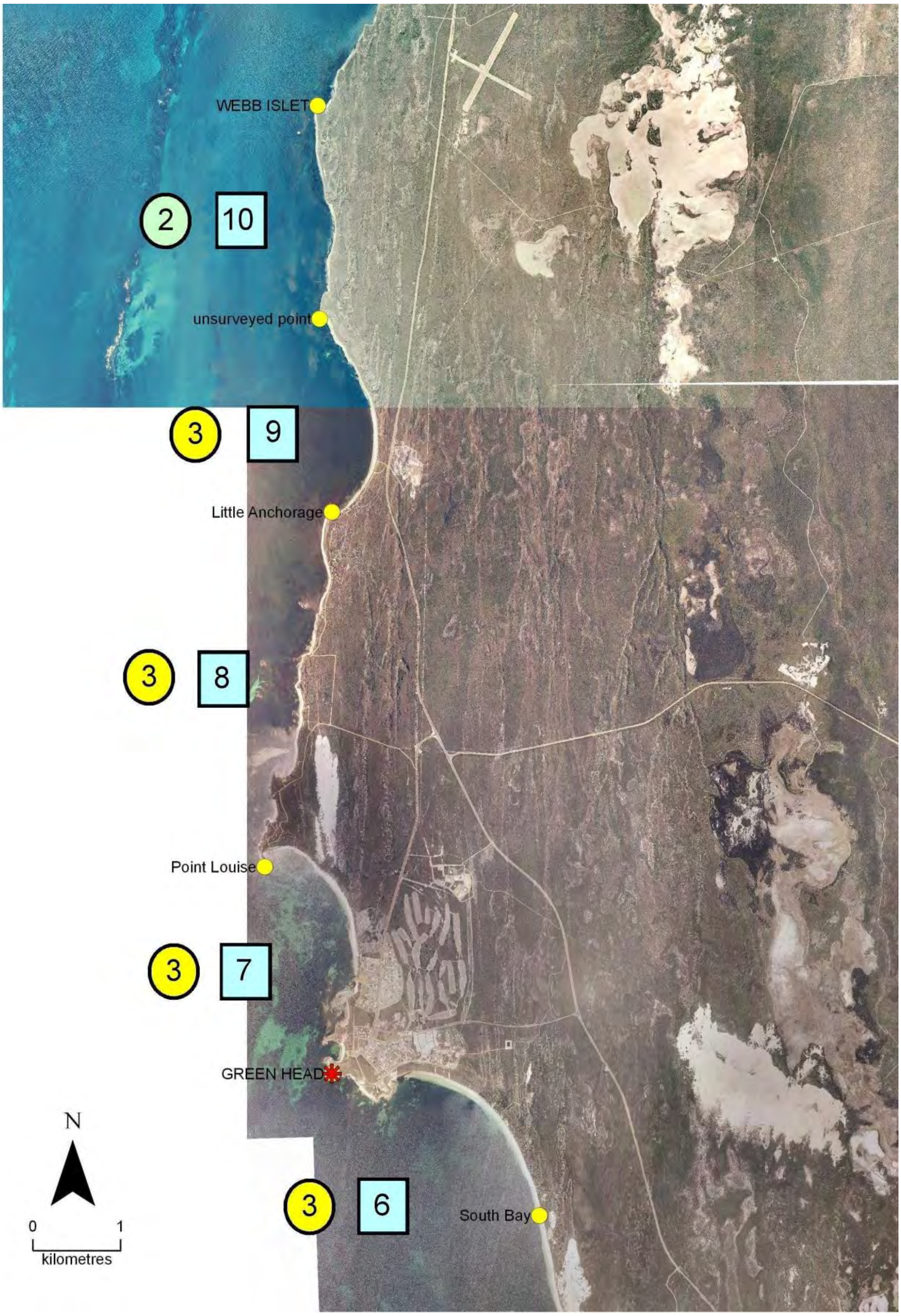

Figure C - 52: Vulnerability for Cells 6-10

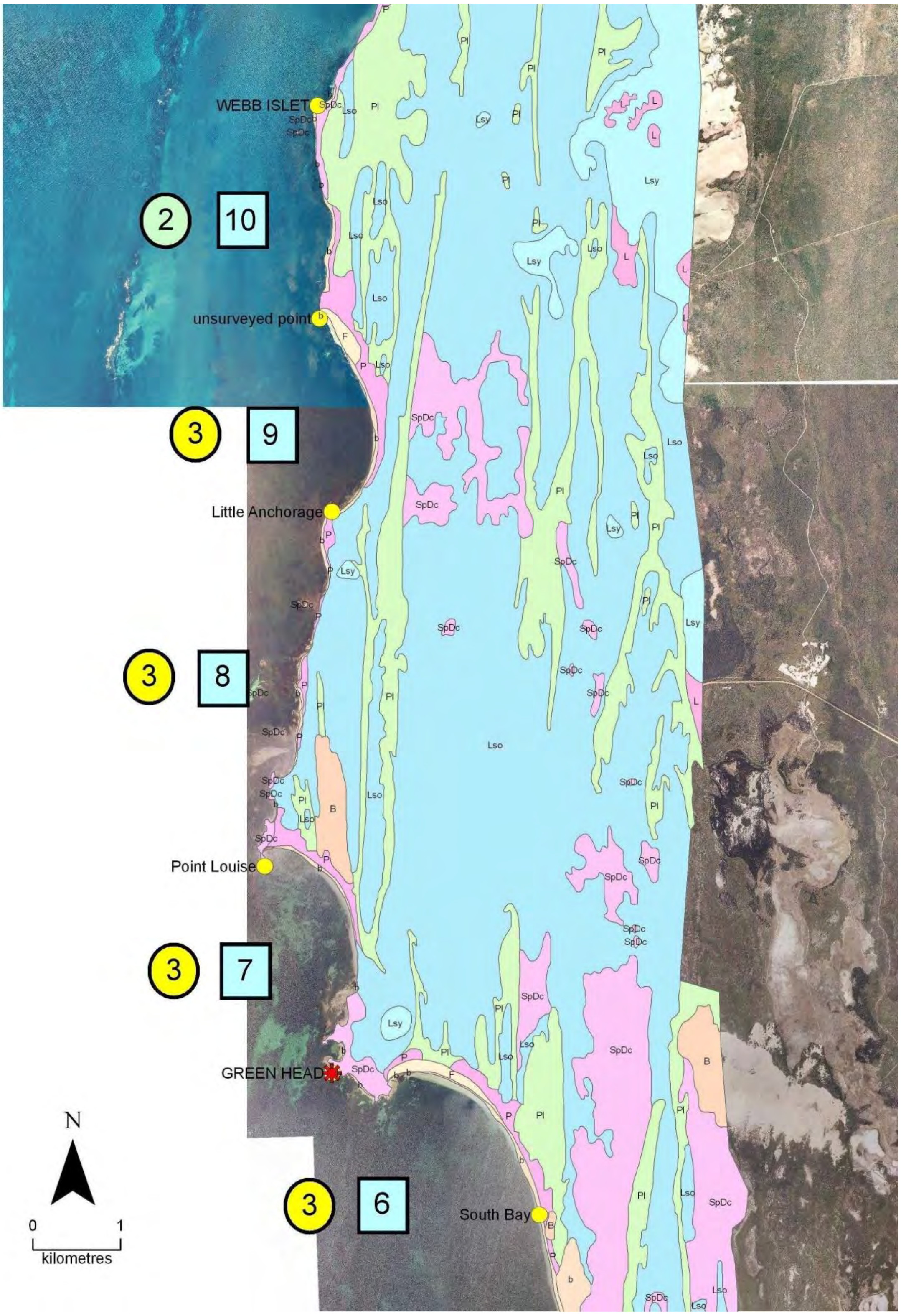

Figure C - 53: Landforms for Cells 6-10

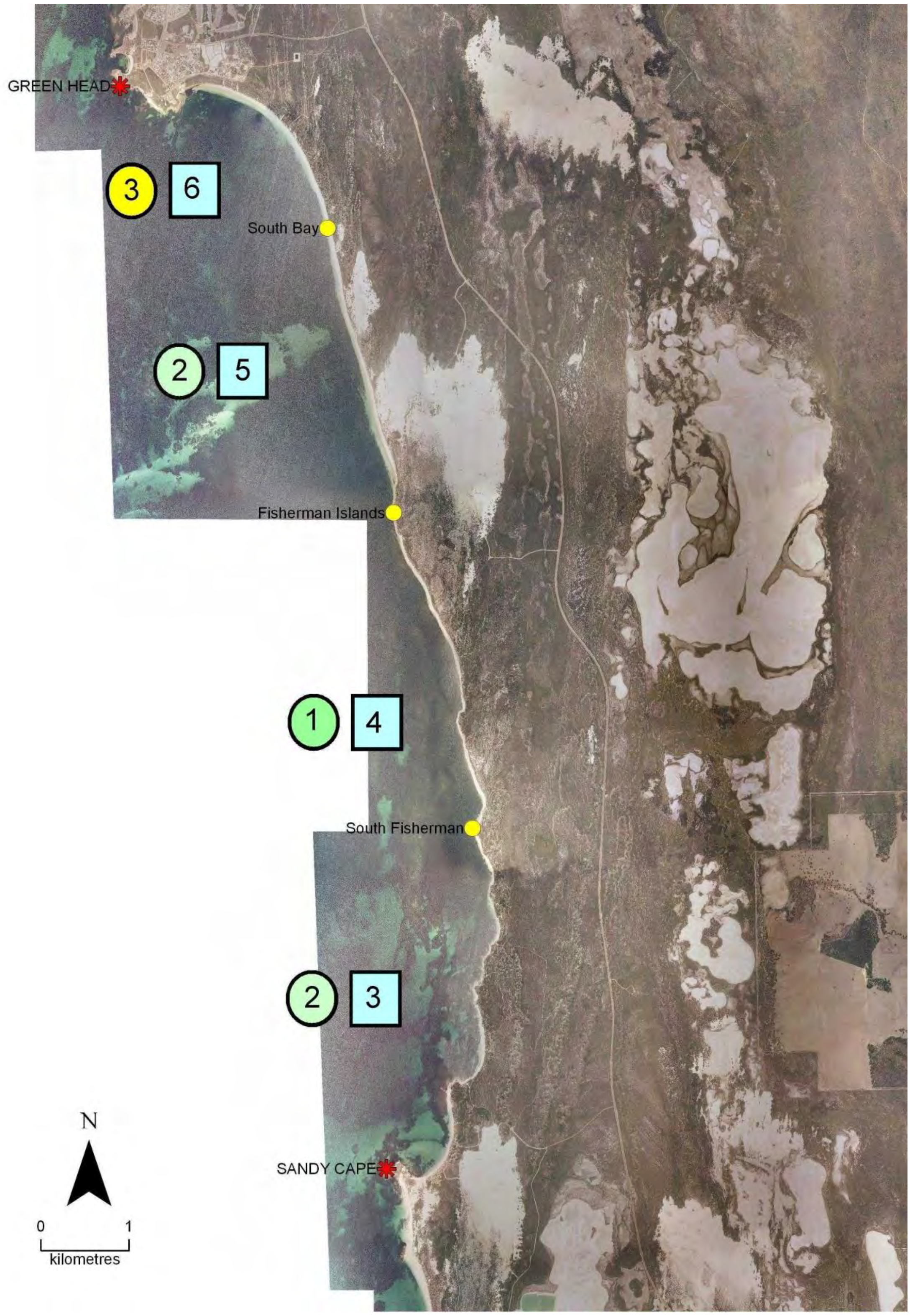

Figure C - 54: Vulnerability for Cells 3-6

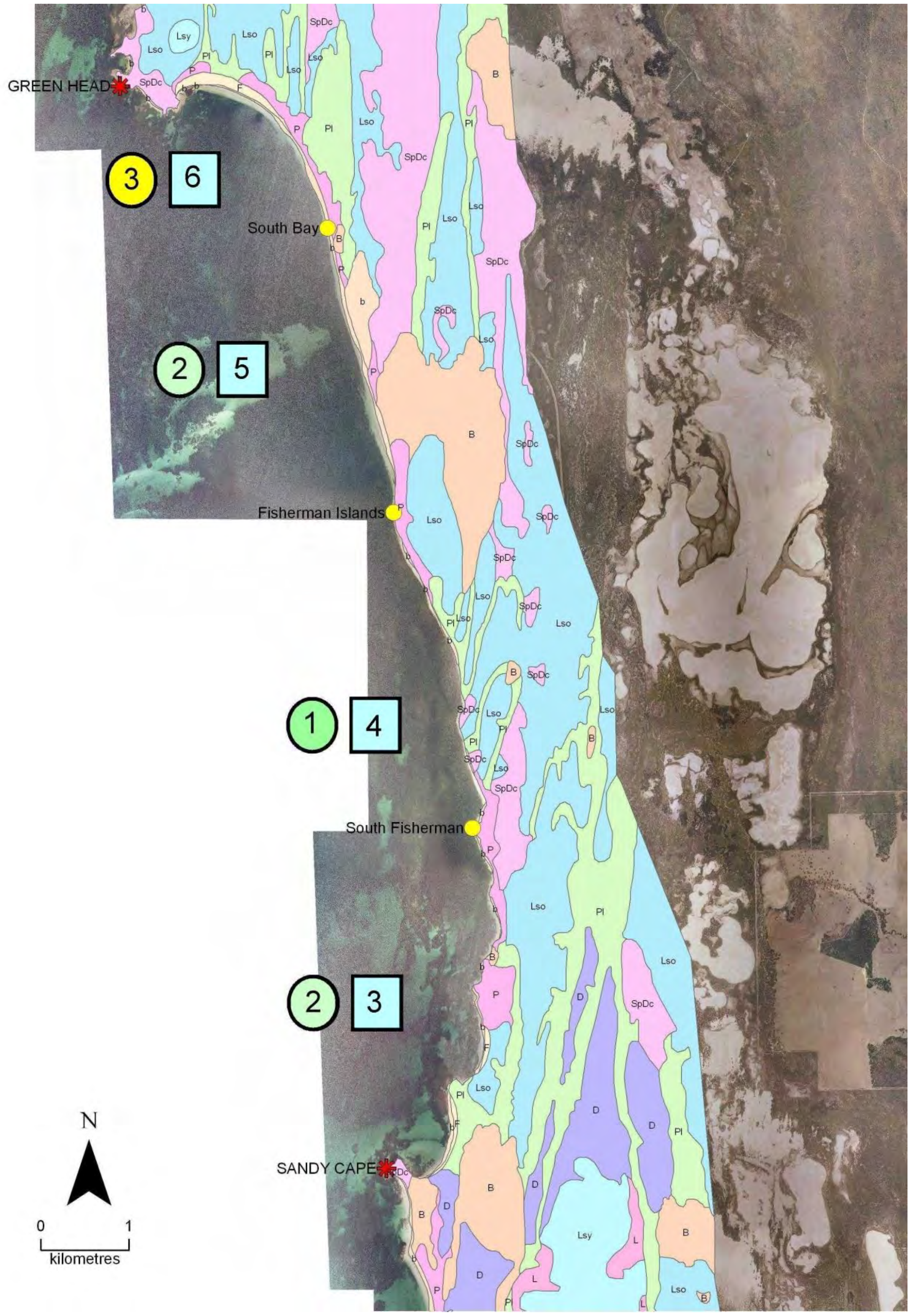

Figure C - 55: Landforms for Cells 3-6

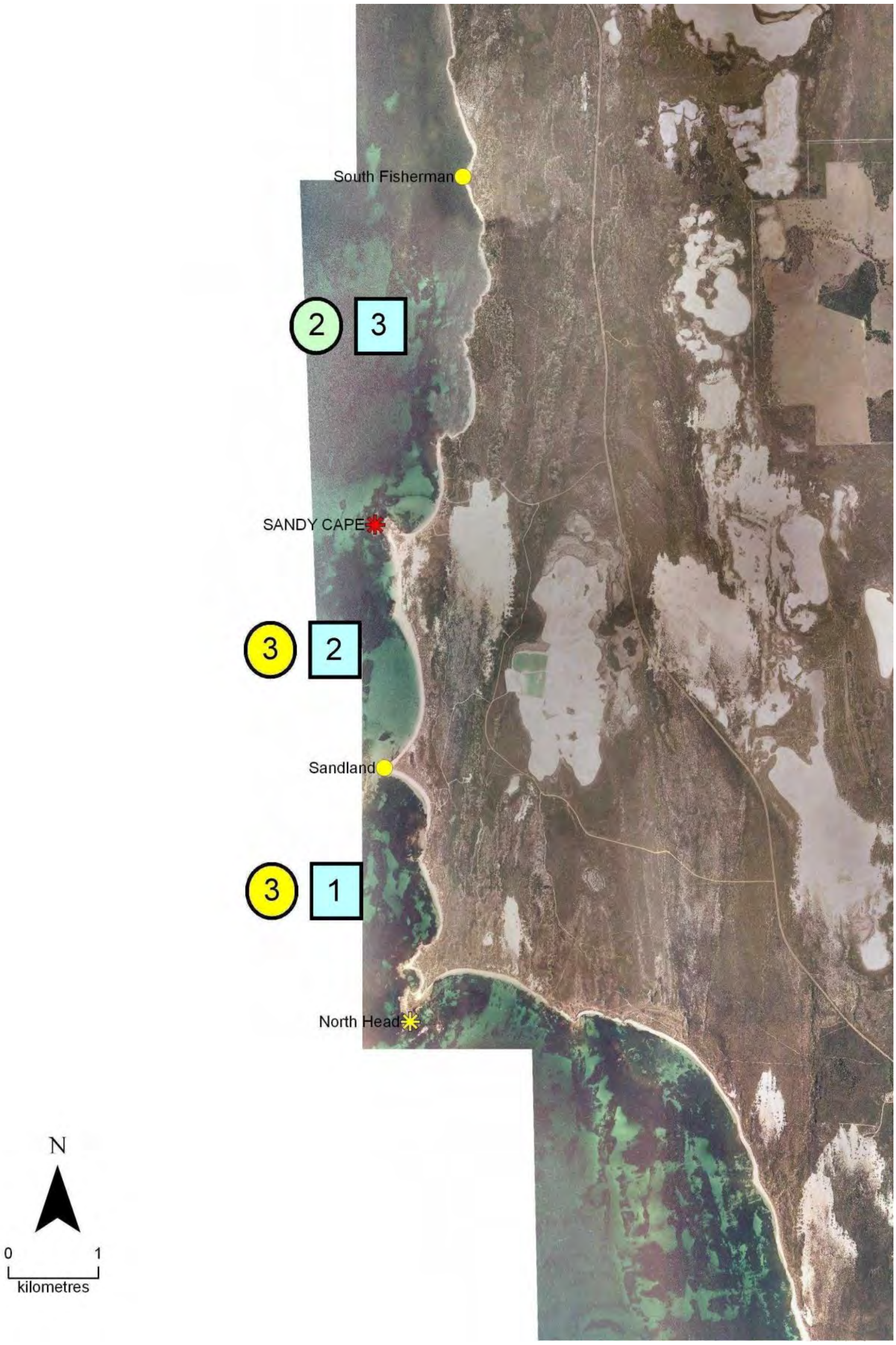

Figure C - 56: Vulnerability for Cells 1-3

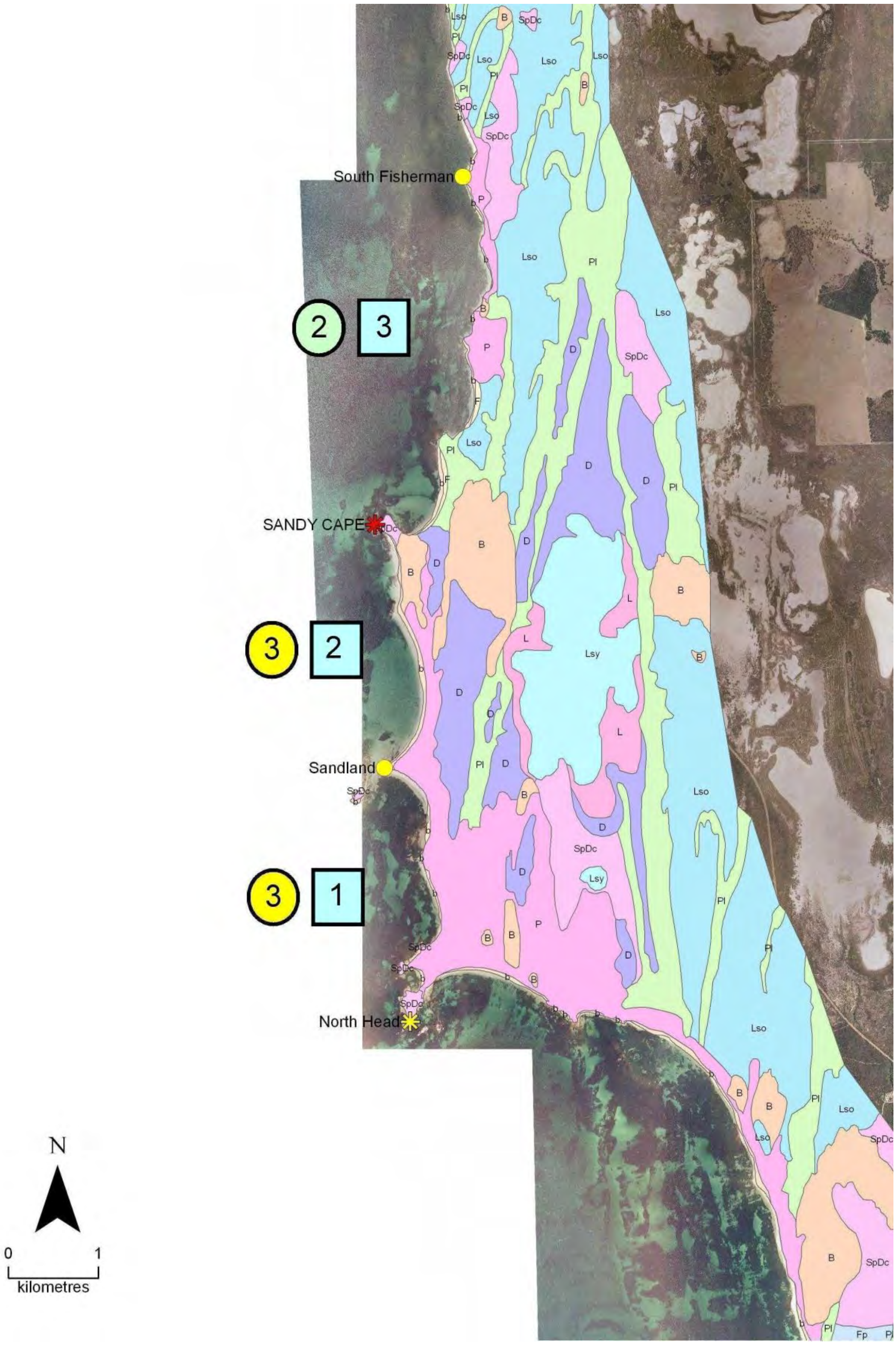

Figure C - 57: Landforms for Cells 1-3

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Appendix B Sediment Cell Descriptions

All location names within this table are based on the three sources listed in Section 6.

Cell	S	N	INSHORE	SHORE	BACKSHORE
64	Murchison River	Nunginjay Spring Coast N	The sediment cell between the mouth of the Murchison River and Nunginjay Spring North identifies coast most affected by river discharge. The inshore bathymetry includes and embayment to the NW of Oyster Reef apparent in the 10 and 15m isobaths. These are within 500m of the shore and include seabed rising to sandstone platform along the coast.	The orientation of the coast changes to a WNW aspect north of the mouth of the Murchison River. The shore has several components: the river mouth with its rock platform and bars; a 5km reach of sandy beach perched on rock platform abutting a rocky coast; and 5.5km of perched beach abutting mobile parabolic dunes. The Beaches are exposed and have a reflective morphology.	Two barrier components form part of the sediment cell north of the river mouth. A mainland beach extends approximately 5km immediately north of the river mouth, with cliff top dunes overlying a calcarenite surface. The foredune on this section of coast has between 25 and 75% cover. Further north are nested parabolic dunes characteristic of an episodic transgressive barrier. This abuts and overlies older dune topography and calcarenite cliffs. The vegetation cover is variable, but generally greater than 50%, and a mobile sand sheet is immediately south of Nunginjay Spring. A high foredune ridge along this section of coast has 25 to 75% cover, small blowouts, and is scarped along its seaward margin.
63	Red Bluff	Murchison River	Between Red Bluff and the Murchison River the 20m isobath is approximately 500m seaward. The seabed rises steeply through intermittent reef and sand to abut a broad sandstone platform.	Two zeta-form (half heart) embayments form the WNW facing coast between Red Bluff and the Murchison River mouth. They are separated by a cliffed sandstone outcrop. The southern embayment is approximately 1km between headlands and supports an exposed, W facing sandy beach with a wave-dominated, reflective morphology. The northern embayment has a rocky shore with sandy beach and dunes intermittently perched on a continuous rock platform. The beaches are wave dominated and have a reflective morphology.	A narrow, up to 500m wide barrier is perched on a rock platform and abuts sandstone cliff. Along much of the coast the dunes have overtopped the cliff and cliff-top dunes are landward of the cliff line. Closer to shore the frontal dune ridge, which essentially comprises a mainland beach barrier, has a vegetation cover >75%. It has been disturbed by access tracks and is scarped along the beach. There are no foredunes.
62	Pot Alley	Red Bluff	The inshore waters between are part of a complex extending to Bluff Point. The 20m isobath is approximately 500m offshore and the seabed rises steeply to a continuous platform abutting a cliffed sandstone coast.	Between Pot Alley and Red Bluff the sandstone coast faces WNW and an irregular cliff falls to a talus slope and deep water. There is no sandy beach on this section of coast.	There is no barrier on this exposed rocky coast. The cliff line is markedly dissected by deep gullies.

Cell	S	N	INSHORE	SHORE	BACKSHORE
61	Bluff Point	Pot Alley	Between Bluff Point and Red Bluff the 20m isobath is approximately 500m offshore and the seabed rises steeply to abut a cliffed sandstone coast. Close to shore the seabed is mainly covered with intermittent reef.	Immediately north of Bluff Point the orientation of the rocky coast changes and the straight, cliffed coast faces WNW. The cliffs are skirted by a wide platform, with widths ranging up to 150m, and deep water.	There is no barrier on this exposed rocky coast.
60	Waygoe Well	Bluff Point	The reach of coast between Waygoe Well and Bluff point is the northern extent of a complex extending from Sandalwood Bay and Bluff Point. The 20m isobath runs parallel to the coast between 1 and 2km offshore. Limestone reef outcrops intermittently within 500m of the shore and a platform extends continuously along the shore.	North of Waygoe Well the W to WSW facing shore is underlain by a continuous rock platform that merges with platform skirting cliffs at Bluff Point. On the landward margin of the platform the exposed beach has a reflective morphology.	An episodic transgressive barrier on which over 75% of the surface is occupied by mobile sand sheets perched on older dune topography. Near Bluff Point the mobile sand sheets overlie a cliff top. There is <25% vegetation cover on the narrow barrier, including the vegetated strip of frontal dune which is scarped along its seaward margin. Foredunes are absent.
59	Waygoe Well South	Waygoe Well	The inshore waters are part of a complex extending from Sandalwood Bay and Bluff Point. The 20m isobath runs parallel to the coast between 1.5 and 2km offshore. Limestone reef outcrops intermittently within 200m of the shore and a platform extends intermittently along the shore.	Between Waygoe Well South and Waygoe Well the rock platform is reduced to a discontinuous line of rock outcrops along the straight, W to WSW facing coast. Small salients are tied to occasional outcrops of rock and there are places where the shore landward of small sections of platform has been eroded. The exposed beaches have a reflective morphology.	An episodic transgressive barrier on which over 75% of the surface is occupied by mobile sand sheets perched on older dune topography. The barrier is narrow, ranging in width from 1 to 1.5Km. The vegetated strip of frontal dune has a 25 to 75% cover and is scarped along its seaward margin. Foredunes are absent.
58	Yanganooka	Waygoe Well South	The inshore waters between Waygoe Well South and Waygoe Well are part of a complex extending from Sandalwood Bay and Bluff Point. Here the 20m isobath runs parallel to the coast between 1.5 and 2km offshore. Limestone reef outcrops intermittently within 200m of the shore and a platform extends continuously along the shore.	The long, nearly-continuous rock platform closes with the straight W to WSW facing coast at Yanganooka and extends northwards to Waygoe Well South. An exposed beach with reflective morphology is perched on the platform	An episodic transgressive barrier on which over 75% of the surface is occupied by mobile sand sheets perched on an older dune topography. The barrier is narrow, ranging in width from 1 to 1.5Km. The vegetated strip of frontal dune has a 25 to 75% cover and is scarped along its seaward margin. Foredunes are absent.

Cell	S	N	INSHORE	SHORE	BACKSHORE
57	Sandalwood Bay	Yanganooka	Between Sandalwood Bay and Bluff Point the 20m isobath runs parallel to the coast between 1.5 and 2km offshore. A limestone reef and platforms outcrop intermittently close to the 5m isobath and within 200m of the shore. Gaps in the reef open to small lagoons such as those at Sandalwood Bay, Halfway Bay and Lucky Bay	This section of the straight W to WSW facing coast has a discontinuous, narrow rock platform extending along the shore. Along much of the coast the beach is separated from the reef by a lagoon up to 0.25km wide. The shoreline on the landward side of the lagoon is rhythmic with salients tied to high rock outcrops. Beaches within the lagoon are sheltered away from gaps in the reef and their profiles rounded. More exposed, reflective beaches occur where the platform is low or broken.	The 1 to 1.5km wide barrier morphology consists of a narrow foredune plain with mound dunes and chenier ridges over lacustrine sediments for approximately 3km in the southern part of the cell. North of that is an episodic transgressive barrier on which over 75% of the surface is occupied by mobile sand sheets perched on older dune topography. Frontal dunes and a foredune ridge have formed in the southern section. These have a 25 to 75% vegetation cover with small blowout dunes between mound dunes along the foredune ridge.
56	Shoal Point	Sandalwood Bay	North of Shoal Point the coast abuts the northern flank of a submarine salient that is identified by the 20m isobath and which closes from 4.5 to 1.5km at Sandalwood Bay. Intermittent outcrops of limestone reef and within the 5m isobath close to shore, and limestone platforms outcrop irregularly along the beach, becoming increasingly common with distance north.	North of Shoal Point and extending to Bluff Point the coast straight and faces W to WSW. Between Shoal Point and Sandalwood Bay the shore is predominantly sandy. Small salients are tied to occasional outcrops of rock in the northern half of the cell. The exposed beach has a transitional morphology with longshore bars and rips present.	The receded barrier consists of a narrow foredune plain with mound dunes and chenier ridges over lacustrine sediments. The vegetation cover is between 25 and 75% on the foredune plain. It is least on the foredune ridge where small blowouts have formed between mound dunes along the foredune ridge.
55	Eagles Nest	Shoal Point	From Eagles Nest (Hillock Point) the 20m isobath increases in distance offshore from 3 to 4.5km and describes a submarine salient extending approximately 6km offshore at Shoal Point. The seabed landward of this irregular boundary gradually shallows to 10m within 1km from shore. It is comprised of less than 25% reef or pavement and is bare sand in the nearshore waters.	Sandy coast between Eagles Nest and Shoal Point is shaped by cuspate forelands at Eagles Nest and Shoal Point. The shore between the flanks of the forelands is straight and faces SW. Its exposed beaches have a transitional to dissipative morphology with a nearly continuous longshore bar.	A narrow episodic transgressive barrier ranging in width from approximately 0.3 to 1.0km impounds the northern sector of the Hutt Lagoon. The barrier is comprised of long-walled parabolic dunes with long axes parallel to the shore. The dunes are active on the southern part of the barrier, where the vegetation cover is <25% and the foredunes scarped. The cover is higher in the north, between 25 and 75%, but the barrier is reduced to a narrow foredune plain with mound dunes.

Cell	S	N	INSHORE	SHORE	BACKSHORE
54	Broken Anchor Bay	Eagles Nest	The trend of the 10m and 20m isobaths is parallel to the shore and extend NW from Broken Anchor Bay to Eagles Nest (Hillock Point). Respectively they are approximately 1.5km and 3km offshore. In the SE half of the cell the 5m isobath is close to shore and the seabed comprised of intermittent limestone reef or pavement. In the northern sector the shore diverges from the reef and forms a narrow lagoon, Port Gregory, that opens to the north.	Although not apparent in the southern of the cell, where it is apparently overlain by the beach and frontal dunes, the SW to SSW facing coast is associated with a line of reef running approximately NW. Beaches along this section of coast are exposed and have a transitional morphology. In the northern section the dunes and beach have been eroded leaving the reef exposed in the nearshore. A shallow arcuate embayment the Port Gregory anchorage, has formed in the lee of the reef, with an exit off Eagles Nest where the orientation of the coast changes. Beaches in the lagoon are sheltered and have a flat or segmented profile.	An episodic transgressive barrier up to 1km wide overlies part of the delta of the Hutt River and an older dune complex. Further north, parabolic and nested parabolic dunes impound the Hutt Lagoon, now a hypersaline lake. The vegetation cover is < 25% in the vicinity of the river mouth where active dunes are common and the foredune has <25% vegetation cover. Elsewhere, there are fewer mobile dunes and vegetation cover on the barrier is high albeit between 25 and 75%. A continuous, scarped ridge of foredunes is present along the rest of the coast. ORV tracks are present on the foredunes between the Hutt Lagoon and the river mouth.
53	Menai Cliffs	Broken Anchor Bay	A narrow, discontinuous ridge of reef extends NW along the seaward margin of an inshore ledge between the shore and the 10m isobath approximately 1km off the Menai Cliffs. The 5m isobath is close to shore and the seabed comprised of intermittent reef.	The line of cliffs forming the 6.5km reach of coast has a low-amplitude convex seaward shape facing WSW. The exposed beach has a transitional to dissipative morphology where it is not perched on rock platform or an older calcarenite dune surface.	A narrow episodic transgressive barrier overlies older dune topography and abuts the cliffs along the coast. It widens from approximately 100m to 250m and from a foredune plain to nested parabolic dunes with distance north. ORV tracks are apparent on the foredune plain to the south. The vegetation cover on the parabolic dunes is between 25 and 75%, with many of the dunes active. The foredune ridge is scarped .
52	White Cliffs	Menai Cliffs	From White Cliffs N to Broken Anchor Bay the 20m isobath trends NW and diverges from the NNW trend of the coast. It is approximately 2km offshore at White Cliffs and 3km by Menai Cliffs. The inshore waters are 10m deep and the seabed comprised of irregular limestone outcrops close to the cliffed shore.	The 3km long line of cliffs forming this part of the SW facing coast includes two shallow embayments separated by a rocky salient. The beach is exposed. Its morphology is reflective and transitional, with bars and rips in some places.	A mainland beach abuts a cliffed rocky coast. There is some limited foredune development on the central salient at the northern end of the cliffs. These patches of foredune are well vegetated and scarped.
51	Whale Boat Cove	White Cliffs	Between Whale Boat Cove and White Cliffs the shoreface between the 20m isobath and the shore widens to approximately 2km and the inshore waters deepen. The 10m isobath is approximately 400m offshore. The seabed is comprised of >75% intermittent reef or pavement.	The SW facing shoreline is straight. It has a narrow, exposed beach with reflective to transitional morphology abutting a foredune plain commonly less than 30m wide.	A mainland barrier comprised of the active beach and narrow foredune plain abuts and overlies the colluvial footslopes of a cliffed, rocky coast.

Cell	S	N	INSHORE	SHORE	BACKSHORE
50	Bowes River	Whale Boat Cove	North of Bowes River the 20m isobath is approximately 2km offshore and parallel to the coast. Closer to shore a ridge of limestone reef initially adjoins the shore but becomes separated from it with distance north. The reef is discontinuous and approximately 300m offshore at Horrocks Beach where it forms a small lagoon.	The shape of the coast between Bowes River and Whale Boat Cove is controlled by a straight nearshore reef. Overall the coast faces SW. The reef has been breached in the centre and a shallow arcuate embayment has formed in the lee of the reef, with an exit to seaward through the gap. North and south of the lagoonal embayment at Horrocks Beach are two broad, low-amplitude salients that abut platform reef. A narrow sandy beach is perched on the salients where it is exposed and has a reflective form. It joins with the beaches in the lagoon where it has a flat or segmented form.	An episodic transgressive barrier overlies and older dune complex between Bowes River and the lagoon at Horrocks Beach. It extends half way into the area immediately landward of the lagoon. The vegetation cover of the nested parabolic dunes in the barrier is between 25 and 75%, with most of the area occupied by active dunes. A narrow foredune ridge has a low vegetation cover and is separated from the parabolic dunes by a bare deflation surface. Further north, parabolic dunes from Horrocks have migrated northwards as an active sand sheet, climbed over and escarpment and dropped into Whale Boat Cove. Vegetation cover on the barrier is between 25 and 75% close to the settlement at Horrocks Beach and less close to Whale Boat Cove where the parabolic dune is active and the frontal dunes and foredunes have been disrupted by ORV tracks.
49	Coronation Beach	Bowes River	The narrow shoreface between the 20m isobath and the shore is continuous between Coronation Beach and the Bowes River. The water depth is <5m close to shore. Lines of limestone reef are parallel to the coast and outcrop as nearly continuous reef and platform along the shore.	A shallowly indented, arcuate shore extends from Coronation Beach to the Bowes River. Its SW facing sandy beach is exposed and bypasses two streams, Oakabella Creek and Woolawar Gully. The beaches are exposed and their morphology mainly reflective but varies locally from a reflective to low-wave transitional form.	The coast has a narrow, commonly < 150m wide, episodic transgressive barrier abutting older dunes and coastal limestone. It is up to approximately 350m wide in the entrances to the two streams. Along much of the coast, particularly its northern third the frontal dune has been eroded by blowouts and a bare deflation hollow separates the vegetated dunes, with <25% cover, from a discontinuous foredune ridge.
48	Buller	Coronation Beach	North of Buller River the 20m isobath is approximately 1.5km offshore and extends NNW parallel to the coast. The seabed rises steeply from the 20m isobath to approximately 500m offshore. Close to shore the water depth is <5m and lines of limestone reef are parallel to the coast and outcrop irregularly along the shore northwards to Oakabella Creek.	A continuous sandy beach facing WSW extends along a between the mouth of the Buller River and Coronation Beach. The shore is the almost straight reach of a 14.5km long zeta-form embayment reaching from Glenfield Beach to Coronation Beach. It has several discrete sections. In the south are two shallow embayments each approximately 3km long. A small, deeper embayment at the mouth of Oakabella Creek separates these from a 2.5km reach of straight rocky coast. The beaches are exposed and their morphology varies locally from a reflective to low-wave transitional form.	In each of the two small embayments episodic transgressive barriers abut a cliffed, older barrier complex. The parabolic dunes in both embayments are active, as are extensive reaches of foredune in them. Where the frontal dunes and foredunes are not comprised of active blowouts or parabolic dunes they have been disturbed by ORV tracks along and across them. The small embayment at the mouth of Oakajee River has been significantly disturbed. The vegetation cover of perched parabolic dunes and the foredunes along the rocky shore is more complete, and varies from 25 to 75%. Depending on the shelter locally provided by inshore rock outcrops the beach morphology varies from sheltered rounded morphology to more exposed transitional morphology with subtidal terraces and rips.

Cell	S	N	INSHORE	SHORE	BACKSHORE
47	Glenfield	Buller	Between Glenfield Beach and the Buller River the seabed rises steeply from the 20m isobath to water depth less than 10m approximately 3km from shore in the centre of the sediment cell. From there the seabed rises more gradually to the shore. In the 500 m close to shore the seabed is mainly bare sand with intermittent outcrops of reef and pavement. Irregular rock outcrops occur along the shore, particularly near the rocky headlands at Glenfield and immediately south of the Buller River.	The cell is bounded by dual salients at its northern and southern ends. Between these the W facing coast forms an arcuate, shallowly-indented bay. The beach morphology gradually changes with distance north, altering from a reflective to a transitional form south of the rocky headland at Glenfield Beach. It is narrow, <20m wide at the southern end and widens to approximately 30m in the north. Large accumulations of wrack may be deposited at the point of inflection along the beach where the shoreline within the embayment changes from facing NW to SW. In the northern third of the embayment approximately the beach is perched on a low soft-rock platform.	Parabolic dunes originating south of Glenfield Beach extend into the urban-residential area at Drummonds Cove. This is separate from the narrow foredune plain currently forming the foreshore reserve seaward of Whitehill Road, The plain extends approximately 0.8km north of Drummond Cove Road and terminates at an active parabolic dune overlying older, vegetated dunes. South of Drummond Cove Road, the foreshore reserve complex is well vegetated, with >75% cover where it has not been disturbed by access tracks and construction of residential dwellings. North of the road, the foredune is discontinuous, scarped and has <25% vegetation cover. It is unstable.
46	Chapman	Glenfield	With distance North, the 20m isobath trends NNE closes to within 2km the coast and the irregular limestone reef joins the shore at Glenfield Beach. The reef encloses the northern lagoonal waters of the Champion Bay. Close to shore the seabed is predominantly sandy with an intermittent 25 to 50% cover of reef or pavement	This is a classic sediment cell with the Chapman River debouching at the updrift end of a 5km long sandy beach and, towards the downdrift end, sediment accumulating in nested parabolic dunes or lost offshore. The arcuate, shallowly indented shoreline faces WSW. The beach morphology gradually changes with distance north, altering from a reflective to a transitional form south of the rocky headland at Glenfield Beach.	The barrier increases in width from a narrow foredune plain close to the mouth of the Chapman River to a 1.3kmwide field of nested parabolic dunes south of Glenfield. The dunes are on the rural-urban fringe with landuse including residential areas, dunes cleared for residential subdivision, a wastewater disposal site dunes cleared for residential subdivision and vegetated dunes with 25 to 75% cover. There are numerous ORV tracks in the dunes, particularly in the swale between the foredune and frontal dune. The foredune is unstable. It is absent from the southern half of the cell and scarped in the north.

Cell	S	N	INSHORE	SHORE	BACKSHORE
45	Saint Georges	Chapman	The 20m isobath is approximately 3.5km offshore and immediately seaward of a 1km wide ridge of irregular limestone reef sheltering the lagoonal waters of Champion Bay. Close to shore the seabed rises from approximately 10m deep to a pavement reef and rock platforms outcropping along the shore.	A straight coast facing W by WNW extends north of St Georges to the mouth of the Chapman River. A continuous sandy beach is perched on and protected by a broad subtidal rock platform in the nearshore waters. The shoreline is rhythmic with low-amplitude salients associated with nearshore rock outcrops. The sheltered beach has a segmented or rounded profile morphology. It becomes more exposed with distance north and the morphology becomes more reflective.	There is evidence of nested parabolic dunes perched on or abutting coastal limestone. However the barrier now supports urban development. Remnants of its frontal dune complex forms the foreshore reserve seaward of Kempton Street. There is >75% vegetation cover on the frontal dunes and low foredune away from areas developed for recreational purposes and access tracks.
44	Marina	Saint Georges	The WNW facing coast is sheltered by a broad ridge of irregular limestone reef approximately 3km offshore. The reef encloses the lagoonal waters of Champion Bay. A narrow, discontinuous ridge extends along the 10m isobath, approximately 2km from shore. From there the seabed rises gradually to a wide sub-tidal and intertidal rock platform.	North of the Marina to St Georges the coast faces WNW. A narrow, commonly <25m wide sandy beach is perched on rock platform and abuts a scarped older land-surface. The beach is eroding as is indicated by the installation of shore stabilisation works; a shore-parallel offshore breakwater and an onshore revetment. Under low wave conditions the beach is sheltered but it is exposed and has a reflective profile morphology when higher sea levels inundated the backshore above the platform.	There is evidence of nested parabolic dunes perched on or abutting coastal limestone. However the barrier now supports urban development. Its frontal dunes have been destroyed and the foredune that originally comprised the foreshore reserve has been wholly eroded along the southern half of the cell and is in retreat along the northern sector.
43	Geraldton East	Marina	As in the adjacent cell to the SW, the inshore waters are sheltered offshore by the broad ridge of irregular limestone reef. Closer to shore the bathymetry shelves from the 10m isobath at the shipping channel to the shore, and the seabed is mainly sand over an irregular limestone pavement.	The Geraldton Marina and small boat harbour occupies this section of NW facing coast.	This section of coast is on the northern close to the approximate junction of the Point Moore tombolo with the mainland. It supports an urban area, the City of Geraldton.

Cell	S	N	INSHORE	SHORE	BACKSHORE
42	Geraldton West	Geraldton East	The inshore waters are sheltered by the broad ridge of irregular limestone reef outcrops extending NNE from Point Moore. Within the Port Precinct and closer to shore the bathymetry shelves approximately from the 10m isobath to the shore in 2km, although disrupted by the shipping channel. The seabed is mainly sand over an irregular limestone pavement.	The NW facing shore is broken into three small beaches by groynes. It is a managed, urban environment. The beaches exposed and have reflective morphology.	This section of coast is on the northern flank of the Point Moore tombolo and is at the approximate junction of the tombolo with the mainland. It supports an urban area, the City of Geraldton. The low foreshore reserve is a built environment increasingly supporting urban infrastructure.
41	Connell Road	Geraldton West	The inshore waters between Connell Road and Geraldton West are part of the Geraldton Port precinct. It is the closest part of the N facing coast to the lagoonal basin of Champion Bay with water depths >10m approximately 3km offshore.	The Port of Geraldton and small boat harbour occupies this section of N facing coast.	The Port of Geraldton is approximately located at the junction of Quaternary and Holocene sediments comprising the northern flank of the Point Moore tombolo. The barrier now supports urban industrial infrastructure.
40	Pages	Connell Road	The coast between Pages and Connell Road is similar to that in the cell immediately to the west and on the northern flank of the Point Moore tombolo. It faces along the broad limestone ridge that curves N to NE to rejoin the coast at Glenfield Beach. The inshore waters N to the shipping channel are slightly deeper than those in the western cell and the shore less protected by rock outcrops.	The NW facing shore is zeta-form (half -heart) in shape. The beach is sheltered by offshore reef within 60m of the shore. It has a flat or segmented profile and widens from approximately 50m to 100m with distance eastward.	The cell forms part of the northern shore of the Point Moore tombolo. It is a managed urban beach constrained by shore stabilisation works and little of the original dune field and its vegetation cover remains intact. The barrier now supports infrastructure for port facilities and recreation as well as pedestrian and vehicle access tracks. The foredune is continuous and fully vegetated.
39	West End	Pages	The coast between Point Moore and Pages is on the northern flank of the Point Moore tombolo. It faces along the broad limestone ridge that curves N to NE to rejoin the coast at Glenfield Beach. The inshore waters N to the shipping channel are shallow and the seabed comprised of 23 to 50% irregular reef or pavement, with a substantial cover of bare sand.	The coast between West End and Pages is separated from the adjoining beach to the east by a long groyne. The N facing beach is comprised of two unconsolidated salients; the West End tombolo and an unattached salient in the centre of the cell. Sand has also accumulated against the groyne. Although exposed to the NNW, the beach is sheltered and has rounded or reflective morphology.	The coast between West End and Pages is part of the northern shore of the Point Moore tombolo. The beach is backed to landward by a 200m wide foreshore reserve comprised principally of a recently prograded foredune plain. The vegetation cover on the plain is at the low-end of 25 to 75%. Some vegetation has been disturbed by vehicle access tracks. The hummocky foredune adjoining the beach have <25% cover and small blowout dunes have formed between the hummocks.

Cell	S	N	INSHORE	SHORE	BACKSHORE
38	Point Moore	West End	The 20m isobath closes with the coast and is approximately 1.5km off Point Moore. The seabed grades steeply to the stacks and irregular limestone platforms comprising the Point Moore Rocks, some of which outcrop at the shore at Point Moore and West End .	Point Moore and West End are compound salients at the western margin of the Point Moore tombolo. They form an arcuate, shallowly indented shore with a westerly exposure. The beach is wide with a reflective to transitional morphology and is perched on rock platform at the apices of the salients.	The foreshore reserve on this part of the Point Moore tombolo is a prograded foredune plain. The vegetation cover is between25 and 75% on the overall reserve and <25% on the discontinuous, hummocky foredune. There is apparent sand drift from the beach into the frontal dune complex.
37	Separation Point	Point Moore	Separation Point is at the northern end of the Tarcoola Embayment. The Point Moore Rocks approximately 2.5km offshore and an extensive limestone platform attached to the shore at Separation Point enclose a small, partly-sheltered lagoonal basin on the southern side of the Point Moore tombolo. The basin is shallow, less than 10m deep, and its seabed has a cover of 25 to 50% intermittent reef.	The coast between Separation Point and Point Moore is a zeta-formed (half-heart) embayment open to the SSW. The beach is exposed and partially affected by shore stabilisation works. It has a transitional morphology with a subtidal terrace and rips.	The sediment cell between Separation Point and Point Moore is the southern part of the Point Moore tombolo, which supports the industrial complex associated with the Port of Geraldton and urban residential areas. The foreshore reserve separating the developed areas from the beach is commonly less than 100m wide. The vegetation cover of the frontal dunes in the reserve is low but between 25 and 75%. It has been disturbed by roads and access tracks. Foredunes are absent and the frontal dunes scarped.
36	Cape Burney North	Separation Point	Southgate Reef and the rocky point at Cape Burney North provide topographic control for the southern end of the Tarcoola Embayment. Between the reef and the shore is a channel less than 10m deep that opens into deeper waters in the embayment further north. The seabed in the inshore waters is between 50 and 75% reef or pavement. The northern end of the embayment is controlled by Separation Point and Point Moore Reef.	A continuous sandy beach extends from the Greenough River mouth to Connell Road where it terminates at Geraldton Harbour. This long beach is The central shore of Tarcoola Embayment is a straight segment facing WSW. The embayment has arcuate sections formed by tombolos respectively facing SW and NW in the north and south. The exposed beach changes from a reflective morphology in the south, where it is in the lee of the Cape Burney North salient, to a wave dominated system with rips, bars and troughs characteristic of transitional beaches.	The mobile sand sheet comprising Southgate Dunes spills into the Tarcoola Embayment at its southern end and one source of sediment to the cell. Southgate Dunes, small area of vegetation adjacent to it and the foreshore reserves along the coast are the only parts of the episodic transgressive barrier not under urban development. The vegetation cover on the frontal dunes in the foreshore reserve is between 25 and 75%. It is lower, <25% in parts of the scarped foredune ridge, particularly in the central part of the embayment.

Cell	S	N	INSHORE	SHORE	BACKSHORE
35	Greenough North	Cape Burney North	A continuous sandy beach extends from the Greenough River mouth to Connell Road where it terminates at Geraldton Harbour. The beach is disrupted by outcrops of limestone reef close to or adjacent to the shore and these identify the limits of smaller sediment cells. Between Greenough North and Cape Burney North the coast is protected by two ridges of continuous limestone reef; Southgate Reef which is approximately 1.5km offshore and an extensive platform along the shore. The seabed between the two reefs is a predominantly sandy channel with irregular outcrops of reef and pavement.	The WSW facing shore between Greenough North and Cape Burney North is topographically controlled by rock platforms and inshore reefs. It is comprised of two salients (tombolos) separated by a small embayment landward of a break in the reef and platforms. The continuous sandy beach is exposed, much of it perched on platform and is has a reflective morphology.	The central third of an episodic transgressive barrier, Southgate Dune, abuts and lies landwards of coastal limestone outcropping along the shore. Approximately 40% of the barrier is non-vegetated mobile sand. The foredune is absent and the frontal dune has been scarped. Its vegetation cover is between 25 and 75%.
34	Cape Burney South	Greenough North	The seabed of the inshore waters seaward of the Greenough River mouth forms a submarine embayment. The outer limit of the embayment is the 20m isobath that trends NW approximately 3km off Cape Burney South and diverges with the coast off Cape Burney North. Further north the reef joins reefs off Point Moore before again closing with the coast at Glenfield Beach. Closer to shore is a channel in the centre of the submarine embayment and the southern end of Southgate Reef approximately 1.5km off Greenough North. Cape Burney South has a high, rocky coast with inshore reef and rock platforms and the inshore seabed has 25 to 50% irregular reef outcrops or pavement, with a greater proportion of bare sand.	There are three distinct components in the coast between Cape Burney South and Greenough North. The southern includes the northern end of the coast between Irwin River and Greenough River. Its rocky shore is comprised of outcrops of fossil coral reef and is an area of geoheritage significance. The rocky shore turns landwards along the left (southern) bank of the Greenough River. The central component is the barred mouth of the river, which is breached during flood events but otherwise provides ORV access between Greenough and Cape Burney South. The northern section is an exposed 1.2km sandy beach facing SW with a transitional to dissipative morphology.	There are two episodic transgressive barrier systems in this cell. The southern barrier complex overlies limestone topography and is well vegetated with the exception of a mobile sand sheet in the centre of the barrier complex and ORV tracks close to the ocean shore. The northern barrier is the southern end of the Southgate Dunes, an extensive mobile sand sheet. Vegetation cover on the barrier complex varies between 25 and 75%, with the active blowouts of the frontal dunes having <25% cover. Foredunes are not well developed and the frontal dunes have been scarped.

Cell	S	N	INSHORE	SHORE	BACKSHORE
33	West Bank	Cape Burney South	The 20 m isobath is parallel to the coast and approximately 1km offshore. The seabed is relatively flatter seaward of the isobath but to landward it rises steeply to the rocky shore. Limestone, including fossil coral reef outcrops irregularly as high platform along the straight shore. Inshore reefs, pavement and platforms control the beach form and provide a structure supporting small embayments with perched beaches and dunes. Modal wave energy is potentially high along this section of coast.	The beach is increasingly narrow and perched above a high rock platform with distance north from the West Bank to Cape Burney South. Here the straight, SW facing coast is exposed and subject to high waves breaking against the shore.	The episodic transgressive barrier is bounded to landward by alluvial flats and the Greenough River. The inland part of the barrier is blowouts with broad, undulating swales. It is well vegetated with 25 to 75% cover. A mobile sand sheet is present in the northern part of the dune field. The frontal dunes have been disturbed by ORV tracks and active blowouts are common immediately landward of the foredune ridge. A high scarped foredune is present in the southern part of the cell but is absent from the north, where the frontal dunes have been scarped.
32	Phillips Road Coast	West Bank	The broad ridge of irregular reef extending to the 20m isobath approximately 7km offshore of Phillips Road Coast terminates abruptly at African Reef and Little African Reef between Phillips Road and West Bank. The broad ridge is replaced by flatter inner continental shelf topography with water depths up to 30 metres until close to shore where the 20m isobath is approximately 1km from the shore. The inshore is predominantly irregular pavement with sand close to shore. Waves break close to the sandy beach.	A continuous sandy beach extends along a straight, SW facing coast. In places the beach is perched on rock platform. It is exposed to high waves breaking at the shore and has a reflective beach morphology.	Although the episodic transgressive barrier is approximately 1.25km wide between Phillips Road Coast and West Bank much of it is a deflation basin and the high dune ridge narrows to less than 0.5 wide near West Bank. The vegetation cover on the barrier varies between 25 and 75% with the lowest cover in the frontal dunes where active blowouts are common. The high foredune is has a low vegetation cover and eroded in places. Much of it is scarped.
31	Lucys	Phillips Road Coast	A broad ridge of irregular reef extends to the 20m isobath approximately 7km offshore between Lucys Beach and Phillips Road Coast. The ridge closes the lagoonal basins extending parallel to the shore further south. The inshore is predominantly irregular pavement with sand close to shore. High waves break close to the sandy shore in a narrow surf zone	The straight, SW facing coast supports a continuous sandy beach. Much of the beach, including a line of storm-tossed boulders, is perched on a high rock platform. High waves break close to the shore in a narrow surf zone. Where the beach is exposed between gaps in the platform and rock outcrops along the shore it has a reflective morphology with a steep beachface profile.	The 0.75 to 1.25km wide, episodic transgressive barrier is high with nested blowouts and parabolic dunes perched on limestone pavement of unknown elevation. Vegetation cover on the barrier is between 25 and 75%. It is and low in the frontal dunes where active blowouts are common, many linked to access tracks; The foredune has is high with a narrow cliffed ridge commonly perched on rock platform.

Cell	S	N	INSHORE	SHORE	BACKSHORE
30	Duncans Pool	Lucys	A 2 to 3km wide ridge of reef extends parallel to the shore and approximately 4.5km seaward. It encloses a small lagoon basin with water depths over 20m. Irregular limestone outcrops, rock pavement and sand patches cover the seabed close to shore.	As with the coast between Nine Mile Beach and West Bank, the shoreline between Duncans Pool and Lucys Beach is straight and faces SW. It is a reach where the discontinuous inshore reef closes with the shore, changing from approximately 200m offshore of Duncans Pool to meet the shore at Lucys. High waves break close to the continuous sandy shore in a narrow surf zone. The exposed beach has a reflective to transitional morphology.	At Lucys Beach the episodic transgressive barrier is at its narrowest and is less than 750m wide. The barrier is high with nested blowouts and parabolic dunes, including bare sand sheets, perched on limestone pavement of unknown elevation. The vegetation cover is on the low sided of 25 to 75%. The frontal dune is high with active blowouts close to shore and disturbed by access tracks. The foredune is continuous and scarped along its seaward margin.
29	Flat Rocks	Duncans Pool	The intermittent ridge of limestone reef extends along the seaward margin of the inshore zone, approximately 4.5km offshore. Off Duncans Pool the ridge widens and its seaward margin is approximately 6.5km from the shore. Close to shore moderate to high wave conditions within the last kilometre from shore interact with a semi-continuous ridge of reef, reef outcrops and rocky pavement to affect beach form and the shape of small embayments .	The SW facing coast between Flat Rocks and Duncans Pool is straight and aligned with shore parallel ridges in the inshore waters. The exposed sandy beach is continuous although disrupted in places by rock outcrops close to shore or underlying platforms. The beach is wave dominated and has a reflective morphology.	The episodic transgressive barrier is approximately 1.25km wide and perched on a limestone basement. Although the vegetation cover is commonly >75%, the vegetation has been disturbed by ORV tracks. The frontal dune complex, including the discontinuous foredune, is moderate to highly unstable particularly on the northern half of the cell. It has been scarped along the beach and the vegetation cover disturbed by access tracks. The foredune is high, and much of it has been scarped.
28	Headbutts	Flat Rocks	From Headbutts to Flat Rock, the ridge of limestone reef is intermittent but continues to form the outer boundary of a lagoonal basin between it and the shore. A continuous limestone reef and shallow lagoon are within 1km of the shore.	Although its orientation remains SW, the sandy beach north of Headbutts narrows from over 30 to 10 metres between the waterline and vegetation line, and its continuity is disrupted by rock outcrops close to the shore or underlying the beach. The beach is wave dominated and has a reflective morphology.	The episodic transgressive barrier is less than 1.5km wide and perched on a limestone basement. Although the vegetation cover is commonly >75%, the nested parabolic comprising the barrier have active slip faces on their landward margin. The frontal dune complex, including the discontinuous foredune, is moderate to highly unstable. It has been scarped along the beach. The dunes have been disturbed by access tracks even though the vegetation cover is between 25 and 75%.

Cell	S	N	INSHORE	SHORE	BACKSHORE
27	Shire Boundary	Headbutts	Approximately 4.5km offshore from the Shire Boundary, the ridge of limestone reef becomes intermittent but continues to form the outer boundary of a lagoon. Further inshore, a ridge of intermittent reef outcrops approximately 0.5km from the shore. It provides moderate to low protection of the shore. The nearshore seabed is sandy.	A shallowly indented, arcuate shore extends from the Shire Boundary to Headbutts. Its SW facing sandy beach is exposed and has a dissipative morphology with rips and bars.	The episodic transgressive barrier is narrow, less than 1.5km wide. It is comprised of nested blowouts and parabolic dunes with some active blowouts close to the cell boundaries and separated from the shore by a vegetated foredune. The vegetation cover on the frontal dune complex is between 25 and 75%.
26	Bookara South	Shire Boundary	A ridge of limestone reef approximately 6km offshore encloses the northern end of a deep lagoonal basin. Within the kilometre close to shore, discontinuous limestone pavement alternates with sand patches so that the beach is moderately to highly exposed to swell.	The SW facing coast between Bookara South and the Shire Boundary is mainly straight with a very shallow, arcuate embayment in the northern half of the cell. The wave-dominated shoreline is rhythmic in plan. The exposed beach has a dissipative morphology with longshore bars and rips.	Two barrier components are apparent; the main ridge of nested parabolic dunes which is approximately 1.7km wide, and a narrower, 3 -500m wide ridge of blowouts that comprise the frontal dune ridge. The vegetation cover on the barrier is between 25 and 75%, with some active deflation areas in both ridges. Closer to shore is a series of high, discontinuous foredunes with approximately 50% cover. The frontal dune complex has been disturbed by ORV tracks.
25	Nine Mile Beach	Bookara South	A ridge of limestone reef encloses the southern part of a basin > 20m deep in this cell. Close to shore irregular reef and pavement deepens and the surf zone widens with distance north from Bobs Hole to Bookara South. The nearshore seabed has approximately 75% sand cover between ridges of reef parallel to the shore.	The shoreline has a shallowly-indented arcuate form. It is zeta-shaped and faces SW. Despite irregular reef outcrops close to shore the coast has an exposed, wave-dominated beach with dissipative morphology and profile configurations. The sandy beach extends continuously from Bobs Hole (Nine Mile Beach) to Headbutts, albeit with minor interruption by rock outcrops at the shore.	The episodic transgressive barrier is comprised of nested parabolic dunes. The dunes are very active close to the coast, with numerous blowouts and mobile sand sheets forming the frontal dune ridge. Further landward the barrier includes deflation basins and has a vegetation cover of >75%. The high foredune ridge is scarped and foredunes absent.
24	Seven Mile Beach	Nine Mile Beach	Between Seven Mile Beach and Bobs Hole at Nine Mile Beach the 20m isobath is approximately 7km offshore. The ridge of limestone reef, which includes Nine Mile Break, trends NNW and parallel to the coast. It becomes more irregular with distance north but continues to enclose a lagoon. Multiple ridges of shallow limestone reef, platforms and stacks shelter the the coast and close with the shore at Bobs Hole.	The shoreline has a shallowly-indented arcuate form and is zeta-shaped to the south. In the south, the beach abuts a 2km long, high platform. The northern section of the coast faces WSW with the nearly continuous beach sheltered by reef close to shore. The exposed, reflective beach is rhythmic with shallowly indented embayments between shoreline salients associated with inshore reef outcrops close to shore.	An episodic transgressive barrier comprised of nested parabolic and blowout dunes overlies a limestone basement of unknown depth and distribution. Its vegetation cover is between 25 and 75%. The frontal dune is partly scarped or steeply faced to seaward, and its 25 to 75% vegetation cover disturbed by numerous access tracks. The foredune is absent from much of the coast, particularly south of Getaway Beach.

Cell	S	N	INSHORE	SHORE	BACKSHORE
23	Harleys Hole	Seven Mile Beach	A continuous limestone ridge extends parallel to the coast and approximately 4km offshore between Harleys Hole and Seven Mile Beach. The reef and the North Bank ridge enclose the southern part of an elongate lagoon with water depths greater than 10m. Close to shore ridges of shallow limestone reefs, platforms and stacks outcrop within 1km of the beach, cover between 25 and 75% of the seabed and shelter the coast.	A continuous, rhythmic sandy beach facing WSW is protected by a nearly continuous inshore reef and rock outcrops. The sheltered beach is rhythmic with shallowly indented embayments between shoreline salients associated with inshore reef outcrops close to shore. Its form varies from rounded to reflective profile configuration with local variation in exposure.	A composite episodic transgressive barrier comprised of nested parabolic dunes is located to landward. Seaward of this is a 250m wide foredune plain. Although there is some disturbance related to access tracks the barrier and frontal dune complex have >75% vegetation cover. The foredunes and frontal dunes are locally scarped in some exposed places between gaps in the reef.
22	Dongara North	Harleys Hole	North Bank is approximately 1.5km off shore from Harleys Hole and forms part of a broad platform separating basins to the north and south. The southern basin is immediately offshore of the sediment cell between Dongara North and Harleys Hole. It is a narrow extension of the deep water off the mouth of the Irwin River. A series of shallow limestone reefs, platforms and stacks outcrop within 0.5km of the shore.	A continuous, rhythmic sandy beach facing WSW extends between Dongara North and Harleys Hole. The beach is shallowly indented between shoreline salients associated with inshore reef outcrops close to shore. Its form varies from rounded to reflective profile configuration with local variation in exposure.	The dune topography indicates a composite barrier with episodic transgressive dunes, including parabolic and nested parabolic dunes overlying a discontinuous rock basement of unknown depth and distribution to landward. Its seaward margin has a narrow foredune plain indicating recent progradation. Both have >75% vegetation cover with low to moderate disturbance related to access tracks.
21	Leander Point	Dongara North	The 20m isobath is approximately 6.5km off the mouth of the Irwin River at Dongara. It is close to the southern limit of the North Bank, a broad ridge of irregular limestone reef extending NW and slightly diverging from the shore it shelters. Inshore exposure is low to moderate in the lee of Leander Reef, high in the vicinity of the river mouth; and moderate to north where further protection is provided by reef and platforms outcropping along the shore.	Away from Port Denison Harbour exposed sandy beaches face mainly WSW. The shoreline is generally straight although broken by small salients associated with outcrops of reef close to shore and by the river mouth. The beaches have a reflective profile morphology which changes to a more transitional form with distance N and increased exposure. Beaches in the northern part of the compartment are sheltered by nearshore reef.	The barrier is comprised of episodic transgressive dunes abutting or overlying discontinuous rock outcrops. Its cover is disturbed by tracking and urban development. South of the Irwin River there is a high, scarped frontal dune. This has been extensively cut at Grannys Pool near the Harbour. Low to moderate to the north. Barrier: With distance N of the river mouth the height of the scarped frontal dune with 25 to 75% vegetation cover decreases, and foredunes have formed.

Cell	S	N	INSHORE	SHORE	BACKSHORE
20	South Leander Point	Leander Point	The 20 m isobath extends northwards and is approximately 7km off Leander Point where it forms the outer limit of a broad ridge supporting Irwin Reef and numerous small irregular outcrops. Waters off Leander Point are commonly deeper than 10 m and form a basin close to shore. The inshore seabed is mainly sandy with 25 to 50% intermittent reef and pavement.	The northern flank of the cuspate foreland at South Leander Point forms a shallowly indented, arcuate embayment that closes with a tombolo at Dongara tied to rocky coast at Leander Point. The sandy beach is continuous from the foreland to its junction with the rocky shore. Although sheltered by the offshore reef complex the fine sandy beach is wave dominated and has a transitional profile configuration with rips and bars.	An episodic transgressive barrier extends from near Cliff Head to the Greenough River at Dongara., where it is approximately 2.5km wide and abuts or overlies coastal limestone. Two parabolic dunes have mobile sand sheets at their landward limit. Both have been cut off from the coastal sediment source by foredune and frontal dune formation. The vegetation cover on the barrier is between 25 and 75%. The frontal dunes and discontinuous foredune ridge are less stable, eroded in places by blowouts and beach erosion. They have less than 25% vegetation cover.
19	White Point	South Leander Point	Seaward of White Point the 20 m isobath is approximately 4km offshore and forms the seaward margin of an irregular ridge running NNW and approximately parallel to the shore. Narrower ridges are closer to shore, one supporting Irwin Reef approximately 2km offshore. Another ridge outcrops at White Tops and Jacks Reef within 1.5km from shore and contributing to formation of the cuspate foreland st South Leander Point. The seabed in the nearshore waters is sandy.	The coast between White Point and South Leander Point is a shallow WSW facing embayment between cuspate forelands. The wave dominated beach is continuous. Its profile morphology varies from a reflective beach near White Point to a transitional morphology with bars and rips as the surf zone widens on the southern flank of a the cuspate foreland at South Leander Point.	The broad episodic transgressive barrier south of White Point continues to the Greenough River. It widens to approximately 7km landward of South Leander Point. Mobile parabolic dunes are attached to the foredune and beach, particularly in the northern part of the embayment. They have been cut along their seaward margins and in most cases separated from the beach by a discontinuous active foredune ridge. Vegetation cover on the barrier is 25 to 75% and less than 25% on the foredune.
18	Cliff Head	White Point	North of the latitude of Cliff Head the 20 m isobath trends NNW to NW, approximately parallel to the shore. It forms the outer margin of a broad ridge of irregular rocky outcrops approximately 3.5km offshore. Two other ridges with a N trend are located closer to shore, including one supporting Horseshoe Reef. The seabed is comprised of 50 to 75% intermittent limestone outcrops and pavement with bare sand and seagrass meadows also present. It is increasingly sandy with distance north in the nearshore waters.	The shoreline plan between Cliff Head and White Point is a long shallow embayment facing WSW. It is bounded by rocky coast at the southern end and a cuspate foreland at White Point. Between these extremes the beach is straight. The fine sandy beach is sheltered although wave dominated with a reflective to transitional morphology.	Change in coastal orientation north of Cliff Head is associated with development of a 4km wide barrier of episodic transgressive dunes, seven with mobile sand sheets at their landward limits. Away from the sand sheets, vegetation cover on the barrier and frontal dunes is between 25 and 75%. Erosion has cut the seaward margin of the parabolic dunes, and a foredune ridge has formed along the backshore. In the southern part of the cell and particularly at White Point in the north, the foredune ridge is seaward of a foredune plain with 25 to 75% vegetation cover and less than 25% on the unstable foredune adjacent to the beach.

Cell	S	N	INSHORE	SHORE	BACKSHORE
17	North Knobby Head	Cliff Head	Approximately 1km north of North Knobby Head the 20 m isobath trends NE and forms a N facing embayment. The seabed gradually shallows from the 20 m isobath to the shore. It is comprised mainly (50 to 75%) of intermittent limestone outcrops such as Hawk Reef and pavement. Bare sand patches and seagrass meadows are also apparent.	A perched beach with flat to rounded profile extends almost continuously along the W to WNW facing coast between North Nobby Head and Cliff Head. In places the continuity of the beach is broken by a limestone headland while elsewhere beachrock is exposed on the landward side of the beaches. The shoreline plan comprises a low-amplitude salient.	The Holocene barrier is largely comprised of a foredune plain less than 200m wide seaward of limestone bluffs which outcrop as higher cliffs in the northern part of the cell. Some older perched dunes are located landward of the bluffs. The foredune plain has 25 to 75% vegetation cover and is eroded along its seaward margin.
16	South Illawong	North Knobby Head	The 20m isobath extends NNE from South Illawong to North Knobby Head. Closer to shore the discontinuous limestone ridge trending approximately NE outcrops as Sandy Bay Reef and Treacherous Bay Reef complexes and is approximately 1.5km off Knobby Head. The seabed in the shallow lagoonal waters between this ridge and the coast includes between 50 and 75% pavement or reef.	A perched beach with flat to rounded profile extends continuously along the WNW facing coast between South Illawong and North Nobby Head. In places beachrock is exposed on the landward side of the beaches. The shoreline plan has two low-amplitude salients with a shallow embayment between them.	The barrier is comprised of older parabolic dunes perched on coastal limestone which outcrops as low bluffs along the coast. The parabolic dune field terminates at the northern end of the cell. Its vegetation cover is 25 to 75% with much clearance on freehold land. A narrow foredune plain separates The limestone bluffs from the shore. Its vegetation cover varies from 25 to 75% and is substantially disturbed by ORV tracks.
15	Gum Tree Bay	South Illawong	North of Beagle Islands the 20m isobath trends NNE and a discontinuous limestone ridge with irregular rock outcrops trends NE. This ridge closes with a narrow reef complex starting approximately 1.5km off Gum Tree Bay. The inshore reef trends NNW and is approximately 2km offshore where it closes with the offshore reef. The sandsheet from the Beagle Island ridge extends approximately 3km north of Gum Tree Bay and is close to shore. Further north the seabed comprises 50 to 75% reef or pavement.	The W facing shore between Gum Tree Bay and South Illawong is at the updrift extremity of sand moving northwards across the Beagle Island ridge. The sheltered sandy beach is nearly continuous and broken only by small rocky headlands. The beach extends along a rhythmic shoreline with low amplitude salients associated with inshore reefs.	The sediment cell is at the northern limit of a wide episodic transgressive barrier, with the older parabolic dune field narrowing from 3.5km to approximately 2km with distance north. Two large mobile dunes are connected to the coast in the central part of the cell. Overall, the barrier has 25 to 75% vegetation cover. The foredunes are partly scarped in the southern section of the cell and absent along the shore near the mobile dunes. A sequence of foredunes ridges with greater 75% vegetation cover is located between the mobile dunes.
14	Coolimba	Gum Tree Bay	The inshore waters shallow with distance north where the lagoonal waters merge with a NE trending ridge linking Beagle Islands to the shore at Gum Tree Bay. Although there are lines of discontinuous limestone outcrops close to shore, there is less than 25% reef or pavement and approximately 50% sand in the nearshore waters between Beagle Islands and the mainland.	North of Coolimba (Desperate Bay) and extending to Gum Tree Bay the WSW facing shoreline is in the lee of the Beagle Island Ridge. The shoreline is rhythmic with low-amplitude salients landward of patches of inshore reef. A narrow, sheltered sandy beach with a flat to segmented profile extends along the coast.	Change in coastal orientation north of Coolimba is associated with development of a 3.5km wide barrier of episodic transgressive dunes over coastal limestone. Although there are some small mobile sand sheets, notably immediately north of Desperate Bay, vegetation cover on the barrier and frontal dunes is between 25 and 75%. There is evidence of foredune erosion and recovery, with small pockets of foredune plain inset in shallow embayments.

Cell	S	N	INSHORE	SHORE	BACKSHORE
13	Tailor Bay	Coolimba	The 20m isobath and offshore reef deepen and trend NNW from Taylor Bay. Irregular rock outcrops occur in the broad lagoonal waters. Closer to shore, the NNE trending ridge becomes more discontinuous and closes with the coast at Coolimba. Near the shore the seabed has pavement, irregular rock outcrop and seagrass meadows. Less than 25% of the seabed is bare sand mainly in elongate sandsheets extending shoreward through gaps in the limestone ridge near the shore.	The coast between Tailor Bay and Coolimba (Desperate Bay) is mainly rocky with sheltered sandy beaches perched on beach rock and pavement within smaller bays bounded by rocky headlands. The W facing shoreline is arcuate in form. It changes from a shallow embayment with a narrow sandy beach with a flat or rounded profile to a broad salient in which smaller beaches are set in small but deeper bays. The beaches are commonly flat and very sheltered although some small beaches such as Bat Cave Cove have a reflective profile.	Episodic transgressive dunes, including long-walled parabolic dunes and blowouts overlie coastal limestone that outcrops as headlands and low bluffs along the shore. Frontal dune and barrier vegetation cover variers between 25 to 75%. ORV tracks are common. Narrow sandy beaches are perched on pavements and platforms along the shore.
12	Leeman	Tailor Bay	The 20 m isobath is on the seaward margin of a N-S trending ridge approximately 4.5km off shore. Other, discontinuous limestone ridges occur between the off shore reef and the shore; the most continuous being a NNE trending ridge approximately 1km off the shoreline. This reef outcrops as stacks on Wilson Reef and Mc Taggart Reef. It provides the offshore limit to a narrow lagoon with seabed pavement, irregular rock outcrops and seagrass meadows. Less than 25% of the seabed is bare sand.	This compartment is an extension of that to the immediate south but includes the townsite at Leeman. The coast extends the shallowly indented arcuate shoreline facing WNW. Shallowly arcuate sandy beaches are perched on rock platforms and pavement between headland outcrops. They are narrow and have a sheltered, flat or segmented morphology.	Vegetation cover on the narrow, perched dunes of the barrier varies from 25 to 75% away from the townsite, and tracks along the coast are common. These have reduced the vegetation cover of the frontal dunes to <25% on much of the coast. Foredunes abutting the small beaches have been scarped by erosion or are absent.
11	Webb Islet	Leeman	In the nearshore waters a continuous limestone ridge extending from Dann Reef to Freezer Bay Reef provides the offshore boundary for an inshore lagoon approximately 2km wide. The seabed within the lagoon has 50 to 75% reef or pavement together with some seagrass meadow.	The predominantly rocky coast between Webb Islet and Leeman forms a shallowly indented arcuate shoreline facing WNW. Some small, shallowly arcuate sandy beaches are perched on platforms and pavement between headland outcrops.	The compartment largely comprises perched parabolic dunes with 25 to 75% vegetation cover overlying coastal limestone. Foredunes abutting the small beaches have been scarped by erosion. Access tracks along the coast and to the small sheltered beaches are common.

Cell	S	N	INSHORE	SHORE	BACKSHORE
10	unsurveyed point	Webb Islet	North of Dann Reef the offshore ridge becomes continuous and encloses a coastal lagoon with water depths over 10m. Close to shore, between the Unsurveyed Headland and Webb Islet, limestone outcrops irregularly as pavement, platforms and stacks	An irregular section of coast with shallowly indented embayments between rock outcrops extends from Unsurveyed Point to Webb Islet. Flat west-facing beaches are sheltered by the reefs and platforms.	Well vegetated nested parabolic and blowout dunes overlie coastal limestone. A foredune plain has formed in the southern part of the embayment. The foredunes have been cut in places and the vegetation cover reduced by beach access tracks. The northern part of the embayment includes a frontal dune ridge of nested parabolic dunes with 50 to 75% vegetation cover. Elsewhere the barrier also has 50 to 75% vegetation cover.
9	Little Anchorage	unsurveyed point	An embayment at Little Anchorage has formed landward of a gap between Becker Reef and Dann Reef. The inshore seabed is comprised of shallow intermittent reef or broken pavement.	A deeply-indented arcuate zeta-form embayment faces west and is located between Little Anchorage and a rocky headland landward of Dan Reef. The beaches are sheltered by the inshore reefs and widen with distance north where they are more reflective in profile.	The arcuate shoreline of the embayment north of Little Anchorage has been eroded into nested parabolic and blowout dunes. A foredune plain has formed in the northern part of the embayment and has 50 to 75% vegetation cover. In the southern part of the embayment the foredunes have been cut and the vegetation cover reduced by beach access tracks. Elsewhere the barrier also has 50 to 75% vegetation cover.
8	Point Louise	Little Anchorage	Approximately 3.5km offshore, the 20m isobath trends NNW to Corner Break Reef. In contrast to this, a narrow limestone ridge approximately 3.5km offshore extends ENE and irregularly outcrops as Bickers Reef. A shallow lagoon, with depths up to 8m, is apparent between this ridge and reef outcropping irregularly as pavement, platforms and stacks close to shore between Point Louise and Little Anchorage. Close to shore, the seabed has > 75% reef or pavement.	The WNW facing shoreline is generally straight but includes shallowly indented, arcuate embayments with sheltered sandy beaches between rocky headlands. The flat beaches are sheltered by the inshore reefs	Long-walled, nested parabolic dunes migrating northwards from Little Anchorage formed an episodic transgressive barrier overlying an older limestone and marl surface. The seaward margin of the barrier has been eroded between rock outcrops at the shore. As a result there is considerable variation in the state of the foredunes and frontal dunes, most of which have 25 to 75% or higher vegetation cover. A mobile sand sheet is located in the southern third of the cell.
7	Greenhead	Point Louise	Two ridges of limestone reef trending ENE outcrop between the 20m isobath and the shore. Close to shore the reef outcrops intermittently and forms the headlands at Greenhead and Point Louise. Between the rock outcrops bare sand is apparent on up to 75% of the seabed.	Small reflective beaches are located at the head of deeply indented W and SW facing embayments around Green Head. Anchorage Bay forms a WSW facing embayment between Green Head and Point Louise. Its beaches are reflective and are sheltered by the Fairweather Reef approximately 1km offshore of the bay centre.	Long walled episodic transgressive dunes and smaller blowouts overlying limestone outcrops have contributed to formation of the Green Head tombolo. Similarly, nested parabolic dunes sourced in Anchorage Bay, extend northwards landward of Point Louise. Urban development occupies most of the barrier in the vicinity of Green Head. Close to shore, the frontal dune ridge has greater than 75% cover where not disturbed by access tracks. The foredune and frontal dunes in Anchorage Bay have 25 to 75% vegetation cover with numerous small blowouts present.

Cell	S	N	INSHORE	SHORE	BACKSHORE
6	South Bay	Greenhead	A shallow ridge with intermittent outcrops of limestone reef extends ENE from the 20m isobath through the Three-way Break to close with the coast at Green Head. In slightly deeper waters between this and the Fisherman Islands ridge to the south, the seabed has 50 to 75% pavement and irregular rock outcrops.	The shoreline of the sandy coast is straight and faces WSW. A substantial volume of wrack has accumulated on the beach. Where not covered in wrack, the beach morphology is flat or rounded.	Long, nested parabolic dunes form an episodic, transgressive barrier apparently overlying an irregular limestone surface. There is between 25 and 75% vegetation cover with active parabolic dunes and mobile sand sheets present. The foredunes and frontal dunes are partly scarped with 25 to 75% cover.
5	Fisherman Islands	South Bay	The shallow offshore reef terminates close to Fisherman Islands. It merges with shallow pavement less than 10 m deep and covering 50 to 75% of the sea bed. A sand sheet extends NE from the end of the reef to within 300m of the shore.	The shoreline of the sandy coast is straight and faces WSW. A substantial volume of wrack has accumulated on the beach. Where not covered in wrack, the sheltered beach morphology is flat or rounded.	Long-walled, nested parabolic dunes form an episodic, transgressive barrier apparently overlying an irregular limestone surface. There is between 25 and 75% vegetation cover with active parabolic dunes and mobile sand sheets present. The foredunes and frontal dunes are partly scarped with 25 to 75% cover.
4	South Fisherman	Fisherman Islands	A broad shallow ridge of limestone extends ENE from Fisherman Islands to the mainland. It is commonly < 5m deep, and forms a discontinuous pattern with intermittent outcrops, especially close to shore.	A narrow sandy beach facing WSW extends along a nearly straight shore. In parts it is perched on rock platform and at one point interrupted by a rocky headland. A substantial volume of wrack has accumulated on the beach. Where not covered in wrack, the beach morphology is flat or rounded.	Long, nested parabolic dunes form an episodic, transgressive barrier overlying an irregular limestone surface. There is over 75% vegetation cover with mobile sands occurring in the northern part of the cell. Frontal dune complex is fully vegetated.
3	Sandy Cape	South Fisherman	Intermittent limestone reef, pavement and unconsolidated sediment occur on the seabed of inshore waters from the latitude of Sandy Point northwards to that approximating the southern extent of the Fisherman Islands reefs. Pavement and platforms are close to shore along the southern section of the coast in this cell, with pavement and intermittent outcrops more common in the north.	The shoreline is rocky, irregular and broken into a series of four small embayments containing sandy beaches. The embayments are zeta formed in shape with the two southern embayments facing WNW and northern embayments facing W and WSW. The reflective southern beach is the northern flank of the Sandy Point tombolo and has unconsolidated sands in its nearshore zone. The other beaches have rounded profiles characteristic of perched beaches.	Long, nested parabolic dunes form an episodic, transgressive barrier overlying an irregular limestone surface. North of the mobile sand sheet near Sandy Point there is greater than 75% vegetation cover. Eroded frontal dunes in the southernmost embayment have been disturbed by ORV tracks but have more than 25% vegetation cover. Elsewhere the frontal dunes are less disturbed and have a more complete vegetation cover.

Cell	S	N	INSHORE	SHORE	BACKSHORE
2	Sandland	Sandy Cape	The seabed of the inshore waters is comprised of a patchwork of intermittent reef, pavement and unconsolidated sediments. The limestone rock outcrops as pavement and platforms close to shore around three headlands that break the shore line into two small beaches. The most extensive pavement and platforms are located along the northern beach.	A continuous beach extends from Sandland to Sandy Point in two embayments. The southern embayment is approximately 1.7km across its mouth facing WNW. The northern embayment is approximately 0.9km long, faces W and is perched on an extensive pavement and rock platform. Both beaches display exposed, reflective and transitional morphologies away from the northern flank of the Sandland foreland.	A mobile sand sheet at the head of a long parabolic dune extending from the south of the Sandland foreland is located on the stationary barrier complex approximately 0.6km landward of Sandy Point. Vegetation cover on the barrier landward of the southern embayment ranges from 25 to 75% and is discontinuous. The range is similar but the discontinuous cover is lower landward of the northern embayment. There is 25 - 75% vegetation cover on the frontal dune complex with tracks and erosion apparent in the southern embayment and blowout prevalent in the northern. One of the blowouts extends northwards across the Sandy Point tombolo into the next cell.
1	North Head	Sandland	The seabed of the inshore waters is comprised of a patchwork of intermittent reef, pavement and unconsolidated sediments. The limestone rock outcrops as pavement and platforms close to shore around five headlands that break the shore line into four small beaches. The Bartle Reef, which lies approximately 1km offshore, together with elongate reefs in the vicinity of North Head and Sandland Island, shelter the coast.	The shoreline consists of two major components separated by rock outcrop. The southern embayment is further divided into two components; a 270 m beach facing NW and a longer zeta formed embayment approximately 800m across the bay mouth. The straight section of the zeta form overlays a rock platform and faces WSW. The northern embayment is an arcuate beach abutting a cuspate foreland in the lee of Sandland Island. The arcuate beach faces SW. beach morphology varies with exposure but are commonly exposed reflective beaches.	Two barrier components are apparent. The first is the large stationary barrier system with its cover of nested parabolic dunes. The dunes are the dominant landforms of the southern beaches. They also anchor a small prograded barrier comprised of foredune ridges that form the cuspate foreland. Vegetation cover in the 500 m landward of the shore is between 25 and 50% but is markedly affected by ORV tracks. The frontal dune complex of the southern beach has 25 - 75% discontinuous vegetation cover. The frontal dune has been cliffed. A rocky cliff extends for over 600m along the central part of the cell. Vegetation cover on the northern beach varies from 25 to 75% and has been disrupted by settlement and tracks.

Appendix C Coastal Rankings and Implications for Coastal Planning and Management for Each Cell

SUSCEPTIBILITY AND INSTABILITY RANKINGS SHOULD NOT BE USED INDEPENDENTLY. BOTH ARE BASED ON SEVERAL CRITERIA AND ARE GUIDES TO THE VULNERABILITY ASSESSMENT

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
64	Murchison River	114.1248	-27.5744	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
63	Red Bluff	114.1408	-27.7444	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
62	Pot Alley	114.1262	-27.7694	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.
61	Bluff Point	114.1046	-27.8497	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.

No.	S	Long.	Lat.	Susceptibility Rank	Susceptibility Implications	Instability Rank	Instability Implications	Vulnerability Rank	Vulnerability Risk	Vulnerability Rationale
60	Waygoe Well	114.1332	-27.9322	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
59	Waygoe Well South	114.143	-27.9699	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
58	Yanganooka	114.1503	-28.0022	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
57	Sandlewood Bay	114.1641	-28.0676	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.
56	Shoal Point	114.1752	-28.1116	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
55	Eagles Nest	114.2391	-28.1875	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
54	Broken Anchor Bay	114.3218	-28.2317	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
53	Menai Cliffs	114.3565	-28.2841	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
52	White Cliffs	114.3758	-28.3034	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
51	Whale Boat Cove (Little Bay)	114.4089	-28.3434	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
50	Bowes River	114.4543	-28.4105	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
49	Coronation Beach	114.5643	-28.5516	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
48	Buller	114.6041	-28.6432	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
47	Glenfield	114.6057	-28.6849	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
46	Chapman	114.6197	-28.7308	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
45	Saint Georges	114.618	-28.7497	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
44	Marina	114.6129	-28.7628	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.
43	Geraldton East	114.6106	-28.7701	Not assessed						
42	Geraldton West	114.6037	-28.775	Not assessed						

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
41	Connell Road	114.5876	-28.7738	Not assessed						
40	Pages	114.5826	-28.7762	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
39	West End	114.5762	-28.7778	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
38	Point Moore	114.5759	-28.7842	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
37	Separation Point	114.5962	-28.79	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
36	Cape Burney North	114.6239	-28.8433	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
35	Greenough North	114.6287	-28.8561	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
34	Cape Burney South	114.6336	-28.8679	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
33	West Bank	114.6656	-28.907	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
32	Phillips Road Coast	114.6897	-28.9342	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
31	Lucys	114.7293	-28.968	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
30	Duncans Pool	114.7522	-28.9891	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
29	Flat Rocks	114.7802	-29.0164	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
28	Headbutts	114.8023	-29.0394	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
27	Shire Boundary	114.823	-29.0588	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
26	Bookara South	114.8508	-29.0893	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
25	Nine Mile Beach	114.8735	-29.1263	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
24	Seven Mile Beach	114.888	-29.1701	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
23	Harleys Hole	114.9015	-29.2123	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
22	Dongara North	114.9148	-29.2416	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
21	Leander Point	114.9145	-29.2765	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
20	South Leander Point	114.9269	-29.3127	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
19	White Point	114.9563	-29.3946	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
18	Cliff Head	114.9967	-29.515	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
17	North Knobby Head	114.9695	-29.6206	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
16	South Illawong	114.9587	-29.7045	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
15	Gum Tree Bay	114.9621	-29.7883	**L**	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	**M**	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	**L-M**	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
14	Coolimba	114.979	-29.8563	**L**	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	**M**	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	**L-M**	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
13	Tailor Bay	114.9803	-29.9235	**L**	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	**M**	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	**L-M**	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
12	Leeman	114.9743	-29.9465	**L**	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	**M**	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	**L-M**	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
11	Webb Islet	114.9634	-29.9731	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
10	Unsurveyed Point	114.9632	-29.9949	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
9	Little Anchorage	114.9642	-30.0147	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
8	Point Louise	114.9556	-30.0508	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.

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				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
7	Greenhead	114.9631	-30.0721	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
6	South Bay	114.9872	-30.087	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
5	Fisherman Islands	114.9944	-30.1162	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
4	South Fisherman	115.003	-30.1486	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.

No.	S	Long.	Lat.	Susceptibility		Instability		Vulnerability		
				Rank	Implications	Rank	Implications	Rank	Risk	Rationale
3	Sandy Cape	114.9922	-30.1833	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
2	Sandland	114.9927	-30.2076	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
1	North Head	114.9952	-30.233	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.