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# 1. Introduction

This document provides information regarding coastal landform vulnerability along the Pilbara coast, to support strategic planning and facilitate more detailed local-scale risk assessments. The project, through collaboration with Geological Survey of Western Australia, identifies land systems and the landforms they contain along the Pilbara coast between the Hope Point in Exmouth Gulf and Tryon Point north of Eighty Mile Beach (Figure 1-1). The study covers a geologically old and geomorphologically complex coastal area in which the interplay of prevalent and extreme meteorologic and oceanographic events over millions of years has left its imprint on the landscape. It is intended to provide input to regional and strategic planning, as well as to 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. Both may be locally obscured by the geological and geomorphological inheritance of the region.

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

For known Areas of Planning Interest, local scale results of the coastal vulnerability analysis have been considered in the context of available planning documents. Coastal planning information has been considered with respect to the general objectives of the *Coastal Zone Policy for Western Australia* (WAPC 2001) and the more specific guidance provided by State Planning Policies (WAPC 2003a, 2006, 2013). For the purpose of advice contained in this assessment, these coastal planning criteria have been used as a benchmark with which to identify coastal management constraints. This approach simplifies the planning process, and hence all study recommendations should be recognised as advice, rather than requirements.

## 1.1. AIMS AND OBJECTIVES

Nationally, Western Australia boasts an enviable diversity of coastal landforms. The diversity includes areas of outstanding beauty such as the World Heritage Area at Shark Bay (Department of Environment and Conservation: DEC 2008) as well as geomorphologically - complex coastal wetlands in the Pilbara (Semeniuk 1996) and estuaries of the south west coast (Brearley & Hodgkin 2005) that are prone to inundation by high tides, flooding and storm surge (Department of Climate Change: DCC 2009). This has been acknowledged through formulation and adoption of the *Coastal Zone Management Policy for Western Australia* (WAPC 2001) and the *Western Australian Coastal Management Plan* (WAPC 2002a). The *Coastal Zone Management Policy* provides objectives for management of the coastal zone and the multiple uses it supports, with the *Coastal Management Plan* providing direction for where the policy should be applied. Operating under this policy and plan are the State Coastal Planning Policy SPP 2.6 (WAPC 2013) that provides advice on calculating coastal setbacks and the Coastal Protection Policy (DPI 2006) which provides a framework for allocation of funding for erosion mitigation works through the Coastal Protection Funding Program. The policies are founded on long-standing governance of the coast by State and Local Government authorities and the well-founded interest and commitment of coastal communities.

Coastal management in Western Australia has long recognised the dynamic nature of coastal environments and its consequences for coastal development and land use. Coastal planning and management policies have been intended to mitigate existing and anticipated management problems in areas subject of coastal hazards through intelligent siting and design of infrastructure based on ongoing scientific research (WAPC 2001). Generally, the policies have provided space for natural coastal change to occur as well as facilitating conservation and recreation in many places around the State. Prior to their formulation, lack of focussed policy or subsequent poor application resulted in considerable cost to Local and State Government through the establishment of land uses dependent on recurrent maintenance or frequent replacement of amenities. The historical shortcoming devolved on-going management and maintenance responsibility to current and future generations. Long standing coastal management problems at Augusta, Busselton, Cottesloe, Cervantes, and Geraldton provide examples of historical management problems that persist today. More catastrophic problems have been experienced with severe flooding and the impacts of tropical cyclones in the Pilbara and Kimberley, as has been demonstrated by repeated destruction and relocation of townsite and jetty facilities at Onslow.

Since adoption of coastal planning policies in the early 1970's, preparation of coastal plans, consultancy projects and local research has substantively added to our knowledge of coastal landforms and the processes shaping them. In the southwest of the State where publically available information is sufficiently detailed to assist mitigation of projected future problems the policies essentially apply McHargian principles (McHarg 1995) to plan land use in the context of the natural environment. While the application of such principles may be more difficult to achieve in the Pilbara the information base has been steadily increasing as a result of environmental review for commercial purposes. Hence an aim of this report has been to review the available information and use it to assess potential land system and landform change over a planning horizon of up to 100 years. However, given the confidentiality and public unavailability of commercial information, there are limitations to the review which are necessarily acknowledged in the text where relevant.

Examination of the coastal geomorphology between Hope Point and Tryon Point involved assessment of aerial photography of the study area; review of geology, land system and landform information; site visits; and a review of relevant and available metocean information. It was conducted at two spatial scales of coastal compartments and sediment cells.

First, land systems and major landform components comprising discrete tertiary coastal compartments of the Study Area (Figure 1-2) were identified and described. *Coastal compartments* are natural structural features. They are primarily related to the regional geologic framework of the coast which exerts structural control on the plan form of unconsolidated coastline. The compartments are secondarily dependent on coastal aspect, land systems, and large coastal landforms such as deltas and cuspate forelands visible at a scale of 1:100,000 to 1:250,000. They are comprised of large scale geologic and geomorphologic features subject to significant changes over decades to millennia. The deltaic structures are controlled by the river network of the Pilbara (Figure 1-3).

Second, *sediment cells* in three nominated areas of planning interest were examined in more detail. Sediment cells are also three-dimensional units (Figure 1-4) that are largely dissociated from the broader compartments in the Pilbara (Section 2.1). Primary and secondary sediment cells have been defined for the Pilbara (Figure 1-4); with tertiary sediment cells defined for the three Areas of Planning Interest (Figure 6-8, Figure 6-16, Figure 6-17 and Figure 6-45). In the context of this report tertiary sediment cells are identifiable at scales of 1:10,000 to 1:25,000 or larger at a more detailed local level. The cells are functionally defined by the likely movement of unconsolidated sediments between source areas and sinks via transport pathways within geologic and geomorphic boundaries. Landforms comprising the cells are likely to change in response to sub-decadal, including seasonal and higher frequency changes, in metocean processes. In part the distinction between compartments and cells also is based on the potential ease of determining a sediment budget from available information.

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

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

Examination of the land systems and landforms was consistent with the brief for the project which is included as Appendix A. For the purposes of this report the aims were to:

(a) provide strategic planning guidance, management strategies and direction on appropriate land uses for future subdivision and development of coastal land broadly in the Pilbara by the identification of compartments defining coastal stability and susceptibility to change; and
(b) determine the vulnerability of landforms in more detail for coastal sediment cells in areas of planning interest.

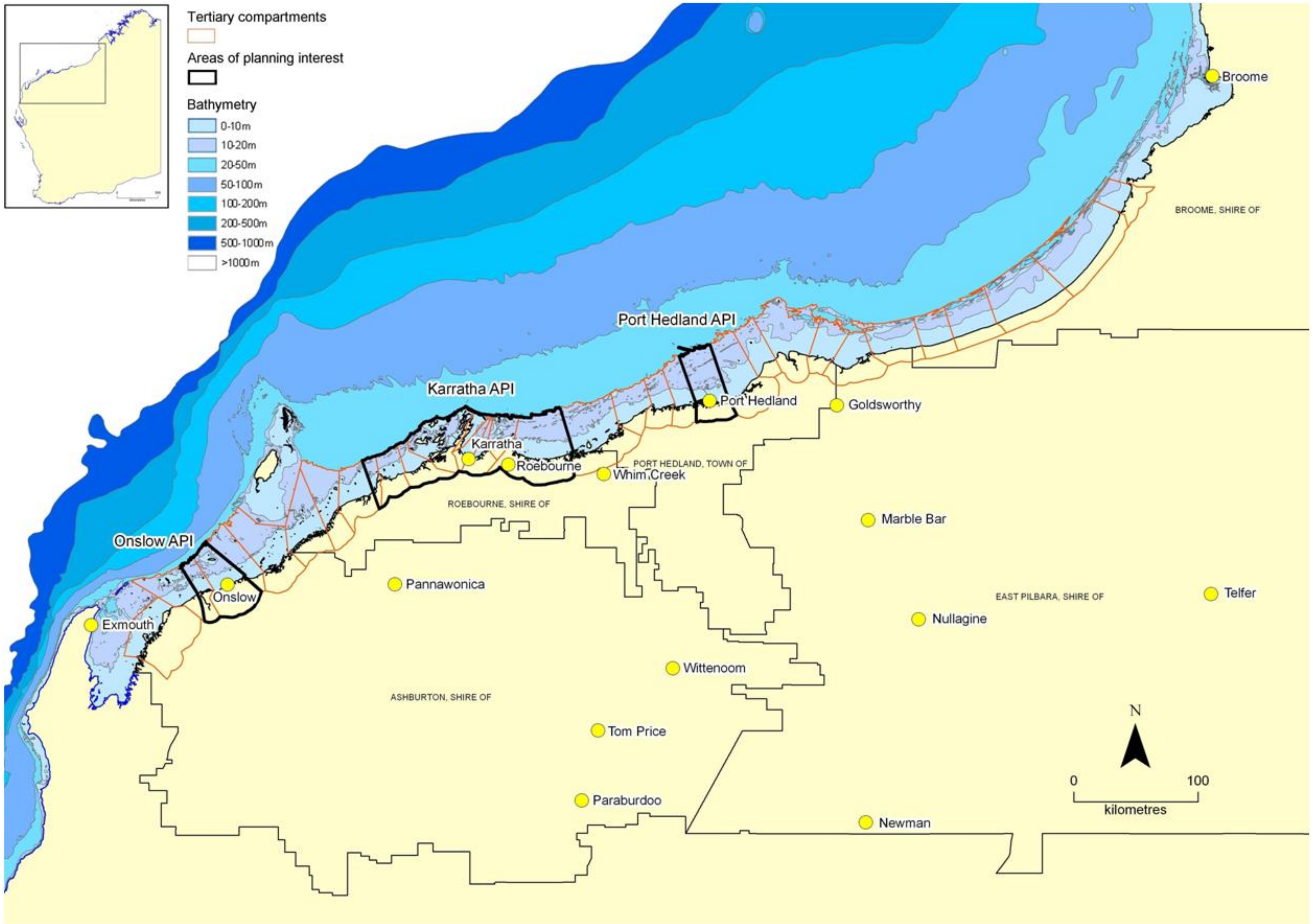



**Figure 1-1: Study Area**

**The Study Area extends from Hope Point to Tryon Point. Tertiary compartments considered for the three Areas of Planning Interest are labelled in black**

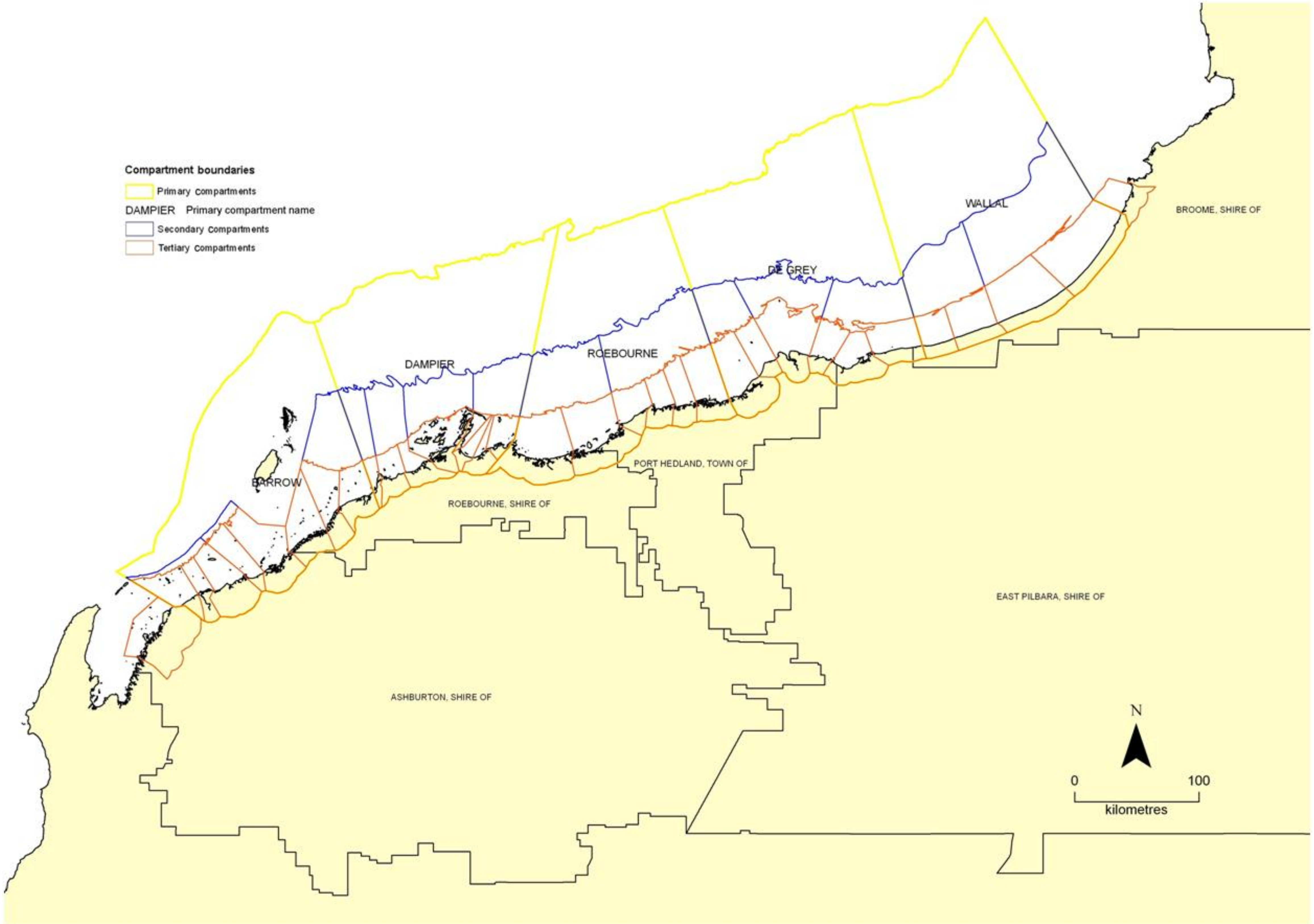



**Figure 1-2: Pilbara Coastal Compartments**

**Offshore boundaries are at the 130m, 50m and 20m isobath for primary, secondary and tertiary compartments (Table 2-5) and correspond with significant geologic features and metocean conditions (Eliot *et al*. 2011a).**

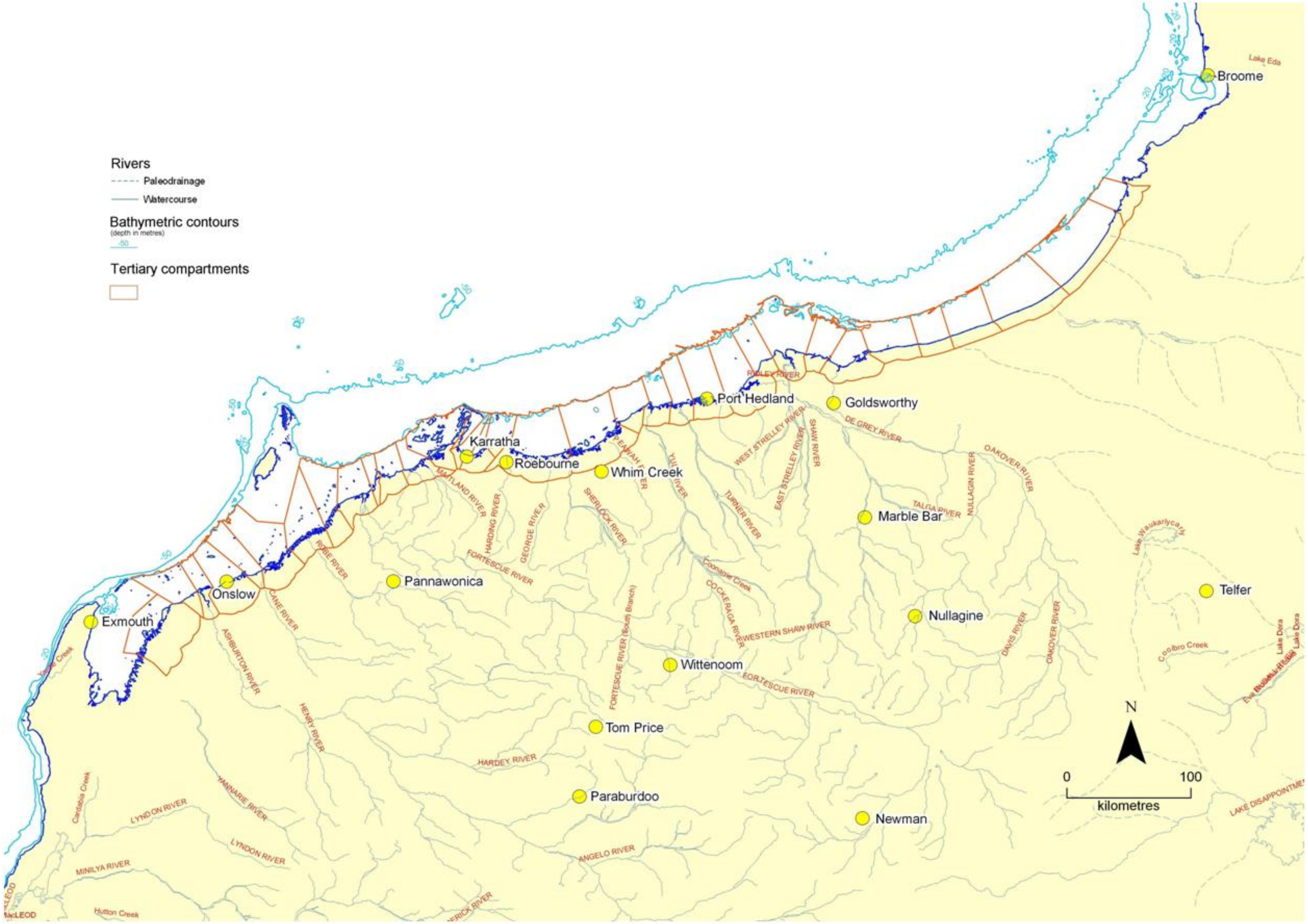



**Figure 1-3: Pilbara Rivers**

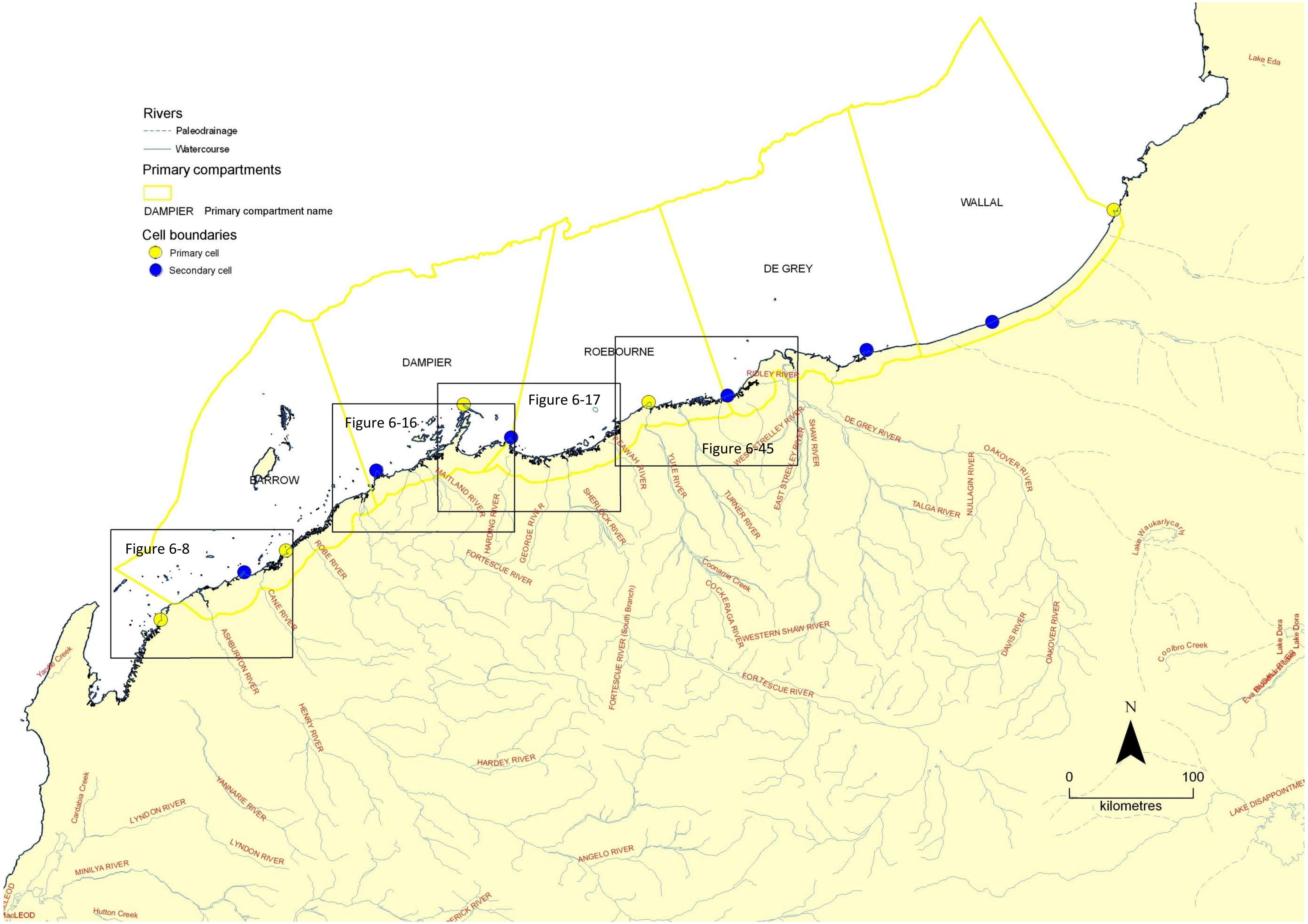



**Figure 1-4: Pilbara Primary and Secondary Sediment Cells and Primary Compartments**

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 Ashburton, East Pilbara and Roebourne, as well as the Town of Port Hedland, in Western Australia (Figure 1-1) at a broad, strategic planning scale. Description of the land systems and landforms comprising the coast is used to provide an indication of potential coastal responses to projected change in metocean forcing. In turn the information presented is intended to identify the nature and degree of investigation required to support management proposals for the land system or landform under consideration.

It was intended these objectives would be met by:

1. First–pass identification and description of coastal land systems across the Study Area; with description of coastal landforms in three Areas of Planning Interest. The description and mapping of coastal landforms is conducted with particular reference to mudflats and coastal lowlands, coastal dunes, beaches, rocky shores and inshore morphology;
2. Broad-scale identification of land systems and large coastal landforms susceptible to risks related to natural variation in climate and sea level fluctuations, and which may be affected by projected changes in climate; and
3. Identify sediment cells within the areas of planning interest and the associated coastal landforms susceptible to risks related to natural variation in climate and sea level fluctuations, and which may be affected by projected changes in climate.

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

## 1.2. KEY PROJECT TASK AND APPROACH

The key project task is to assess the potential vulnerability of coastal land systems and landfoms to variation of metocean processes, wither through natural variation or the effects of projected climate change. A high level assessment (at tertiary coastal compartment scale) has been developed for the strategic coastal planning in the Shires of Ashburton, East Pilbara and Roebourne as well as the Town of Port Hedland. This assessment builds on the landform and land system analysis techniques developed for the Shires of Gingin to Exmouth (Eliot *et al.* 2011b, c, d) to assess coastal vulnerability to changing metocean processes.

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

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

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

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

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

The projected changes of interest are those spanning two time and space scales; short (sub-decadal) and long (over a planning horizon of 100 years) term changes occurring at tertiary compartmental (approximately 1:50,000) and tertiary sediment cell (approximately 1:25,000 or more details) 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 (2003a, 2013);
2. It has been applied to coastal or marine management elsewhere in Australia (NSW Government 1990; Government of South Australia 2006; Rollason & Haines 2011) and overseas (Kelley *et al.* 1989; Hart & Bryan 2008; and Whitehouse *et al.* 2009a, b); and
3. A method of analysis can be developed for consistent application at all levels in the hierarchy.

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

## 1.3. DOCUMENT USE

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

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

# 2. Methods

Coastal vulnerability was estimated as follows:

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

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

## 2.1. IDENTIFICATION OF PLANNING UNITS

The hierarchy of compartments and sediment cells comprise two sets of planning units, coastal compartments (Table 2-1; Figure 1-2) and sediment cells (Table 2-2; Figure 1-4; Figure 6-8; Figure 6-16; Figure 6-17 and Figure 6-45). This report focuses on tertiary compartments and tertiary sediment cells. In the context of this report they are areas sharing physical features apparent at mapping scales respectively appropriate to regional and local planning. At each scale the approach used focused on description of the structural framework provided by the geology, and to a lesser extent, large geomorphic features formed of unconsolidated sandy sediment.

Four sets of features were used to identify the alongshore boundaries of coastal compartments. These are listed in Table 2-3 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 2-4. Onshore, the boundary of the compartments was taken to be the landward extent of alluvial coastal land systems. Alternatively, for compartments and cells the boundary 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 2-5) provide an approach to interpretation and implementation of the State Coastal Planning Policy SPP 2.6 (WAPC 2013) and/or the Coastal Protection Policy (DPI 2006).

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

**Table 2-1: Compartments**

Areas of Planning Interest: + Port Hedland, ^ Karratha and * Onslow

| Primary Compartment | Secondary Compartment | Tertiary Compartment |
|---|---|---|
| PINDAN: Cape Jaubert to Swan Island (Extends beyond Study Area) | Cape Jaubert to Cape Villaret (Extends beyond Study Area) | Cape Jaubert to Tryon Point |
| WALLAL: Shoonta Well to Cape Jaubert | Eighty Mile Beach Caravan Park to Cape Jaubert | Samphire Bore to Cape Jaubert |
| | | Eighty Mile Beach Caravan Park to Samphire Bore |
| | Shoonta Well to Eighty Mile Beach Caravan Park | Cooraidegel Well to Eighty Mile Beach Caravan Park |
| | | Shoonta Well to Cooraidegel Well |
| DE GREY: Beebingarra Creek to Shoonta Well | Condini Landing to Shoonta Well | Cape Keraudren to Shoonta Well |
| | | Mulla Mulla Creek to Cape Keraudren |
| | | Condini Landing to Mulla Mulla Creek |
| | Yan Well to Condini Landing | Yan Well to Condini Landing |
| | Beebingarra Creek to Yan Well | Wattle Well to Yan Well |
| | | Beebingarra Creek to Wattle Well |
| ROEBURNE: Cape Lambert to Beebingarra Creek | Cape Cossigny to Beebingarra Creek | + Downes Island to Beebingarra Creek |
| | | West Turner River to Downes Island |
| | | Cape Thouin to West Turner River |
| | | Cape Cossigny to Cape Thouin |
| | Cape Lambert to Cape Cossigny | Sherlock to Cape Cossigny |
| | | ^ Cape Lambert to Sherlock |
| DAMPIER: James Point to Cape Lambert | Dolphin Island Point to Cape Lambert | ^ Cleaverville Creek to Cape Lambert |
| | | ^ Karratha Back Beach to Cleaverville Creek |
| | | ^ Cinders Road to Karratha Back Beach |
| | | ^ Dolphin Island Point to Cinders Road |
| | West Intercourse Island to Dolphin Island Point | ^ West Intercourse Island to Dolphin Island Point |
| | Cape Preston to West Intercourse Island | ^ Pelican Point to West Intercourse Island |
| | | ^ Cape Preston to Pelican Point |
| | James Point to Cape Preston | ^ James Point to Cape Preston |
| BARROW: Locker Point to James Point | Peter Creek to James Point | Mount Salt to James Point |
| | | Peter Creek to Mount Salt |
| | Coolgra Point to Peter Creek | Weld Island to Peter Creek |
| | | Yardie Landing to Weld Island |
| | | Coolgra Point to Yardie Landing |
| | Locker Point to Coolgra Point | * Hooley Creek to Coolgra Point |
| | | * Bare Sand Point to Hooley Creek |
| | | Locker Point to Bare Sand Point |
| EASTERN GULF: Giralia to Locker Point (Extends beyond Study Area) | Giralia to Locker Point (Extends beyond Study Area) | Hope Point to Locker Point |

**Table 2-2: Sediment Cells**

Tertiary cell considered for Areas of Planning Interest at: + Port Hedland, ^ Karratha and * Onslow

| Primary Cell | Secondary Cell | Tertiary Cell | Focal Area |
|---|---|---|---|
| Cape Thouin to Cape Jaubert | Eighty Mile Beach Caravan Park to Cape Jaubert | | |
| | Cape Keraudren to Eighty Mile Beach Caravan Park | | |
| | Petermarer Creek to Cape Keraudren | | |
| | Cape Thouin to Petermarer Creek | 22. Cooke Point to Petermarer Creek + | Beebingarra |
| | | 21. Spoil Bank (W) to Cooke Point + | Old Hedland |
| | | 20. Finucane to Spoil Bank (W) + | Hedland Harbour |
| | | 19. Downes Island to Finucane + | Islands |
| | | | |
| Cape Legendre to Cape Thouin | Cape Lambert to Cape Thouin | | |
| | | 18. Reader Head to Butcher Inlet (E) ^ | Point Samson |
| | | 17. Point Samson to Reader Head ^ | |
| | | 16. Cape Lambert to Point Samson ^ | |
| | Cape Legendre to Cape Lambert | 15. Rocky Ridge to Cape Lambert ^ | Cleaverville-Anketell |
| | | 14. Anketell to Rocky Ridge ^ | |
| | | 13. Jockeys Hill to Anketell ^ | |
| | | 12. Fields Creek to Jockey Creek ^ | |
| | | 11. Nickol Bay Mine to Fields Creek ^ | Karratha |
| | | 10. Karratha to Nickol Bay Mine ^ | |
| | | 9. Nickol Bay (W) to Karratha ^ | |
| | | Sloping Point to Nickol Bay (W) | |
| | | | |
| Port Weld to Cape Legendre | Cape Preston to Cape Legendre | | |
| | | Dampier to Searipple Passage | |
| | | 8. Sharp Peak to Dampier ^ | Dampier |
| | | West Intercourse Island (W) to Sharp Peak | |
| | | Regnard Bay to West Intercourse Island (W) | |
| | | Pelican Point to Regnard Bay | |
| | | 7. Little Hill to Pelican Point ^ | Cape Preston |
| | | 6. Cape Preston to Little Hill ^ | |
| | Port Weld to Cape Preston | 5. Preston Spit to Cape Preston ^ | |
| | | 4. James Point to Preston Spit ^ | |
| | | | |
| Urala Creek to Port Weld | Coolgra Point to Port Weld | | |
| | Urala Creek to Coolgra Point | 3. Beadon Point to Coolgra Point * | Onslow |
| | | 2. Hooley Creek to Beadon Point * | |
| | | 1. Rocky Point to Hooley Creek * | |
| | | | |

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.

**Table 2-3: 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 |

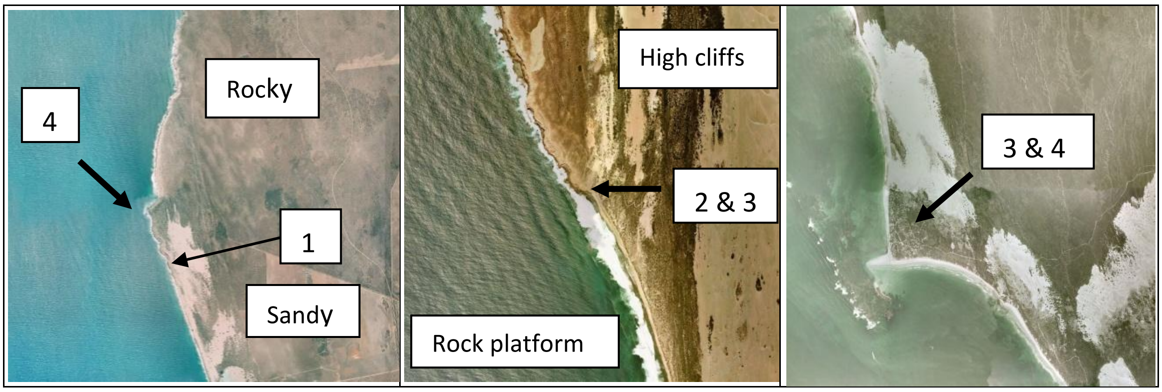
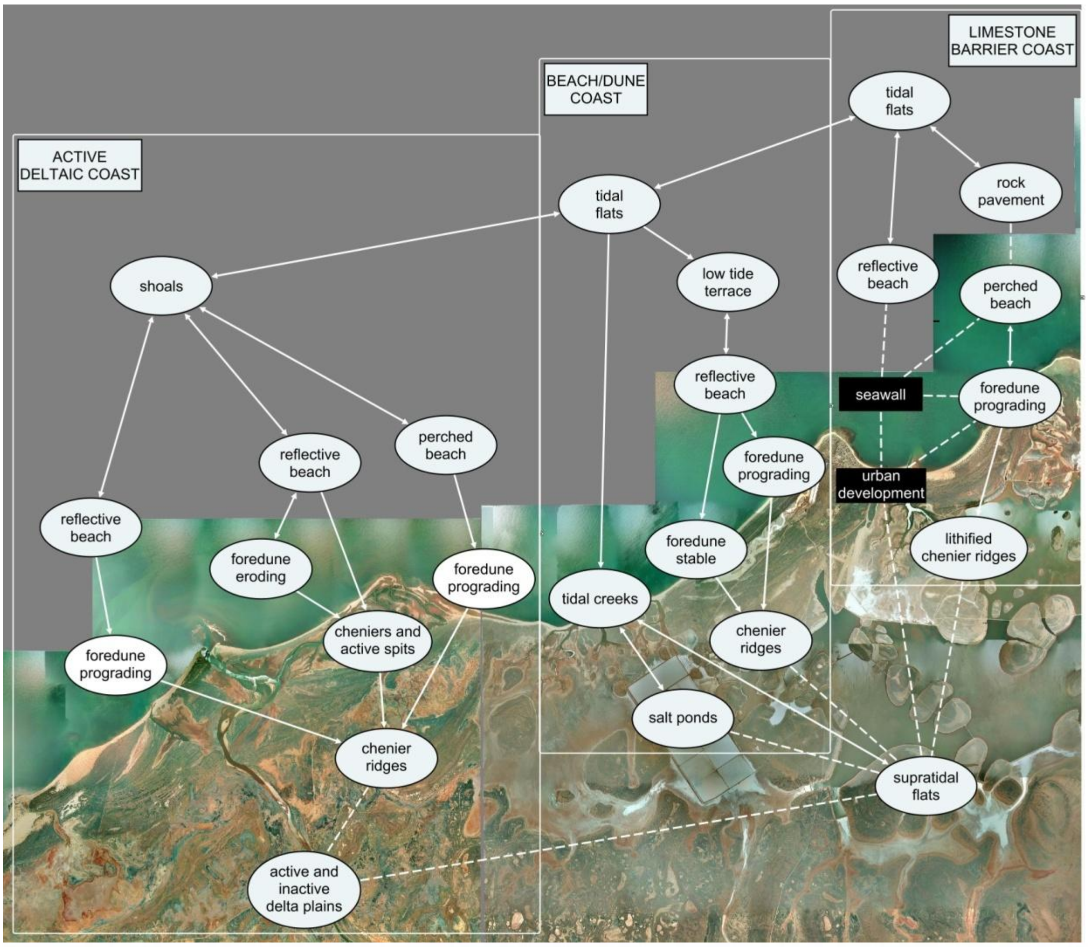



**Figure 2-1: Examples of Compartment Boundaries**
**1 = change in geology; 2 = rock structure; 3 = geomorphic feature; and 4 = change in aspect**
**⟶ = Primary boundary ⟶ = Secondary boundary**

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 compartment boundaries and 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 association between sediment budget estimation and coastal management (eg. Hooke *et al.* 1996; Cooper *et al.* 2001).

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



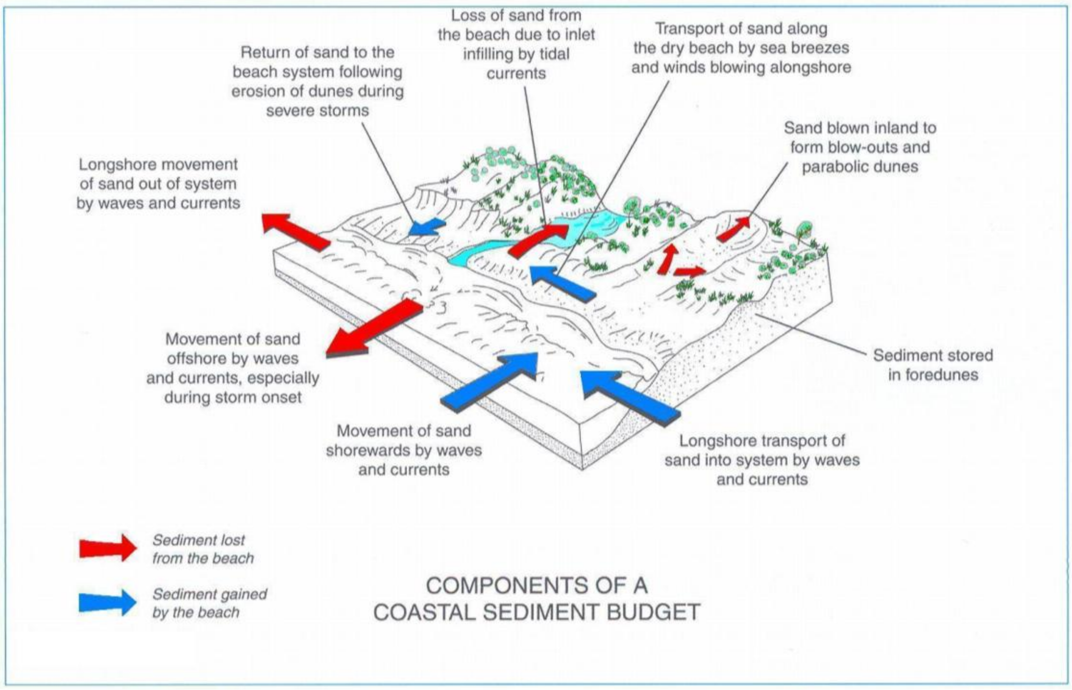




**Figure 2-2: Sediment Budget Components**
**(A) Components of a sediment cell at Onslow and Hooley Creek; and (B) a conceptual sediment cell in which the components of the sediment budget have been identified Estimation of the volume of material for each component would contribute to determination of a sediment budget for the cell (Source: WAPC 2002a)**

**Table 2-4: Coastal Compartments and Cell Scales with Potential Management Application**

| Boundary (isobath) | Land System/Landform Scale and Geology | Management Application |
|---|---|---|
| **Primary Compartments** (130 metres) | Mega-scale land systems<br>e.g. Barriers, river deltas, zeta-form beaches<br>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.<br>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<br>e.g. Cuspate forelands, tombolos and dune sequences<br>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.<br>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.<br>e.g. beaches, foredunes and blowouts.<br>Inshore topography landward of the 20m isobath determines the nearshore wave regime and current patterns that drive the coastal sediment budget. It has a direct effect on the stability of coastal landforms, particularly those comprised of unconsolidated sediment. Coastal changes are apparent at seasonal and interannual to decadal scales. | The inshore waters and coastal lands are critical for provision and maintenance of marine based infrastructure (harbours and marinas). In addition to its commercial value, the area comprises a substantial proportion of State Waters and is highly significant for coastal recreation.<br>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.<br>e.g. seagrass beds, scour channels, longshore troughs, beaches and mobile dunes.<br>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 2-5: 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<br>(State or Region) | Continental shelf boundary<br>(250m isobath) | Broad scale geology & coastal land systems | Climate zone & global weather scales such as the Walker Circulation & Southern Oscillation | Broad-scale tidal environment;<br>Deepwater wave environment;<br>Geographic variation in major ocean currents | Main natural structural features & landscapes;<br>Broad-scale (geologic) evolution of the coast |
| STRATEGIC PLAN<br>(Primary Compartment) | Interglacial low sea level<br>(130m isobath) | Shoreface geological structures & coastal land systems and form patterns<br>(eg. Episodic transgressive sand barrier) | Distribution of major weather systems affecting the region, including those associated with extreme events | Broad-scale tidal regime;<br>Inter-annual and long-term variation in mean sea level;<br>Deepwater wave environment;<br>Outer shelf current regime | Geological development of major land systems apparent at a regional scale<br>(eg. barrier type) |
| REGIONAL PLAN<br>(Secondary Compartment) | Present day shoreface<br>(50m isobath) | Sub-regional geologic framework & large geomorphic responses<br>(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);<br>Seasonal to inter-decadal fluctuation in mean sea level;<br>Inner-shelf wave & current regime | Landform patterns<br>(eg. nested dunes on a barrier);<br>Broad changes occurring to coastal landforms at seasonal, inter-annual and inter-decadal time scales |
| LOCAL or SITE PLAN<br>(Tertiary Compartment) | Inshore sediment movement<br>(Offshore 20m isobath) | Local geologic framework, geomorphologic structures & individual landforms<br>(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;<br>Seasonal and inter-annual fluctuation in mean sea level;<br>Nearshore wave & current regimes | Landforms and landform elements;<br>Description of shoreline movement and landform change at sub-decadal intervals;<br>Local dynamics in response to metocean processes |
| **LOCAL or SITE PLAN<br>(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;<br>Seasonal and inter-annual fluctuation in sea level;<br>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. These vary considerably in terms of extent and detail covered. Many additional studies of local geology and geomorphology have been conducted for site-specific projects. The studies include:

- Coastal management plans (DCE 1985; Chalmers 1986; Astron & Coastwise 1998; DPUD 1992, 1994; Middle G & Hames Sharley 2004; Shire of Roebourne 2007)
- Coastal and marine conservation plans (CALM 1990, 2005; MPRSWG 1994; DEC 2005, 2007, 2011);
- Regional and local development planning strategies (WAPC 1998a, 1998b, 2003b, 2009; Department of Housing & Works 2006; Taylor Burrell Barnett 2011);
- Technical reports (Beard 1975; Eliot & Riches 1981; Craig 1983; Le Provost, Semeniuk & Chalmers 1986; Sinclair Knight & Partners *et al.* 1987; Payne *et al.* 1988; Payne & Tille 1992; GEMS 2000a, b; Harris *et al.* 2003; van Vreeswyk *et al.* 2004; Parsons Brinckerhoff 2005; Straits Salt *et al.* 2005; Simpson *et al.* 2007; GEMS 2008c, 2009; Damara WA 2010a, 2011a, 2011b; Eliot & Dodson 2010; URS 2010; JDA *et al.* 2011a, b; Oceanica & Damara WA 2011; Gozzard 2012a);
- Data summary reports (Osborne *et al.* 2000; Heyward *et al.* 2006; Jackson *et al*. 2006; Baker *et al.* 2008); and
- Scientific papers (Woods *et al.* 1985; Semeniuk 1986, 1993, 1996, 2008; Short 2005).

Consideration of landforms is required for development plans in the region (WAPC 2012) as well as for the Shire of Ashburton (DoP 2010a), Shire of Roebourne (DoP 2011a) and Town of Port Hedland (DoP 2011b).

Further studies with some consideration or anticipated documented landforms, land systems or geomorphology include those addressed in Environmental Protection Authority (EPA) reports for Yannarie Salt (EPA 2008a), Onslow Salt (EPA 1991a, 1995a, b, 1997a, b), Macedon pipeline (EPA 2010a), Wheatstone (EPA 2011a; Chevron Australia 2010), Griffin pipeline (EPA 1993), Cape Preston (EPA 2002, 2006a, 2009a), Dampier Port expansion (EPA 2003a, 2006b), Anketell Point (EPA 2003b, 2005, 2012a), Cape Lambert (EPA 2007, 2010b), Dampier Salt/Leslie Salt (EPA 1991b) and port and dredging projects in Port Hedland (EPA 1997c, 2008b, c, d, 2009b, d, 2010c, 2011b, 2012b; BHP Billiton 2011).

These provide substantial insight into the variety and distribution of landforms along the coast, and some describe different sectors of coast based on landscape. Few cover large tracts of coast or have adopted a compartmental or sectoral approach to landform description as a basis for planning. However, they identify the major land systems and landforms present in the Study Area (Table 2-6) and have been used in the estimation of coastal vulnerability to metocean changes (Section 4).

Land systems have been mapped and described for the Study Area to 10km landward of the Landgate Mean High Water Mark, extending further inland to incorporate the Holocene and Alluvial Land Systems in the three Areas of Planning Interest (Figure 3-3; Appendices C-D).

**Table 2-6: Major Landform Associations**
**(After: Semeniuk 1996 and Gozzard 2012a)**

| Cross-Shore Location | Landform Association | Landforms |
|---|---|---|
| **(1) Inner Shelf Morphology** | Inner continental shelf | Linear reefs, irregular reef, rocky pavement, submarine ridges, canyons, shoals |
| | Islands | Terrestrial forms plus linear reefs, irregular reefs, rocky pavements, submarine ridges, canyons, shoals |
| **(2) Subtidal Shoreface** | Islands | Terrestrial forms plus fringing reefs and shoals |
| | Gulfs and embayments | Deep embayments, shallow embayments, zeta-form bays, irregular embayments |
| | Reefs | Linear reefs, pavement reefs, submarine ridges |
| | Basins and lagoons | Lagoon, sand banks, cuspate forelands, sand flats, and seagrass meadows |
| | Subtidal terraces | Tidal channels, subaqueous levees, channel gorge, distributary fans, sand ridges, sand bars |
| **(3) Intertidal Shore** | Peninsulas and promontories | See other landforms, including cliffs and rocky terrain |
| | Rocky coasts | Cliffs, bluffs; ramps, platforms, beachrock ramps |
| | Sandy coast | Wave dominated beaches, sheltered beaches, tide dominated beaches, perched beaches, storm ridges, spits and cheniers |
| | Deltas, rivers and inherited basins | River mouths, cheniers, tidal creeks, tidal flats beachrock ramps |
| | Tidal flats and tidal creeks | Supratidal flats, salt flats, residual mounds and hillocks, tidal creeks, levees, tidal channels, palaeochannels |
| **(4) Backshore Landforms** | Rocky terrain | Limestone cheniers, ridges and outcrops |
| | Deltas | Floodplains, outwash plains, linear or longitudinal dunes, rivers, streams, alluvial flats, distributary fans, palaeochannels, pools, billabongs, tidal flats |
| | Estuaries | River channels, levees, tidal flats, sand bars |
| | Coastal lagoons and wetlands | Bedrock and residual sand islands, river deltas, distributary fans, palaeochannels, pools, tidal flats |
| | Salt marsh | Tidal channels, ridges, cheniers; marsh; mangroves |
| | Tidal flats | Salt flats, algal flats, bioturbated flats, tidal creeks, overbank basins |
| | Inherited basins | Bedrock and residual sand islands, river deltas, stream distributary fans, palaeochannels, pools, tidal flats |
| | Outwash plains | Linear dunes and ridges, palaeochannels, stream distributaries, bedrock and residual sand islands |
| | Barriers | Episodic transgressive, prograded, stationary, receded, perched barriers and mainland beach |
| | Foredunes | Continuous ridge, discontinuous ridge, blowouts, scarped foredunes |
| | Frontal dunes | Blowouts, parabolic dunes, frontal dune ridge, mobile sand sheet |

Four areas of landform development are commonly identified. These are the inner shelf, subtidal shoreface, intertidal shore and backshore or components of the marine and coastal environment. Herein *inner shelf* refers to the shelf morphology to 20m depth, corresponding to the offshore boundary of the tertiary compartments; *subtidal shoreface* encompasses the presence, coverage and type of rock in the subtidal area (<20m) and inshore (<5m) along with the orientation of embayments with respect to the dominant surge direction; *intertidal shore* refers to the rock in the intertidal zone, the number of tidal creeks and type and size of river catchments; and *backshore* incorporates the onshore structures including barriers, rocky topography and landforms of fluvial or tidal origin. A different suite of landforms may be identifiable at a regional, land system and landform scale for the same reach of coast.

Detailed maps of onshore landforms have been compiled for the Areas of Planning Interest (Figure 2-3) and used in the assessment of vulnerability at a sediment cell scale. Information relevant to landuse on *specific landforms* has been derived from several sources for local area planning but could be extended from the following sources:

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

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

## 2.3. RANKING LAND SYSTEM AND LANDFORM SUSCEPTIBILITY AND INSTABILITY

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

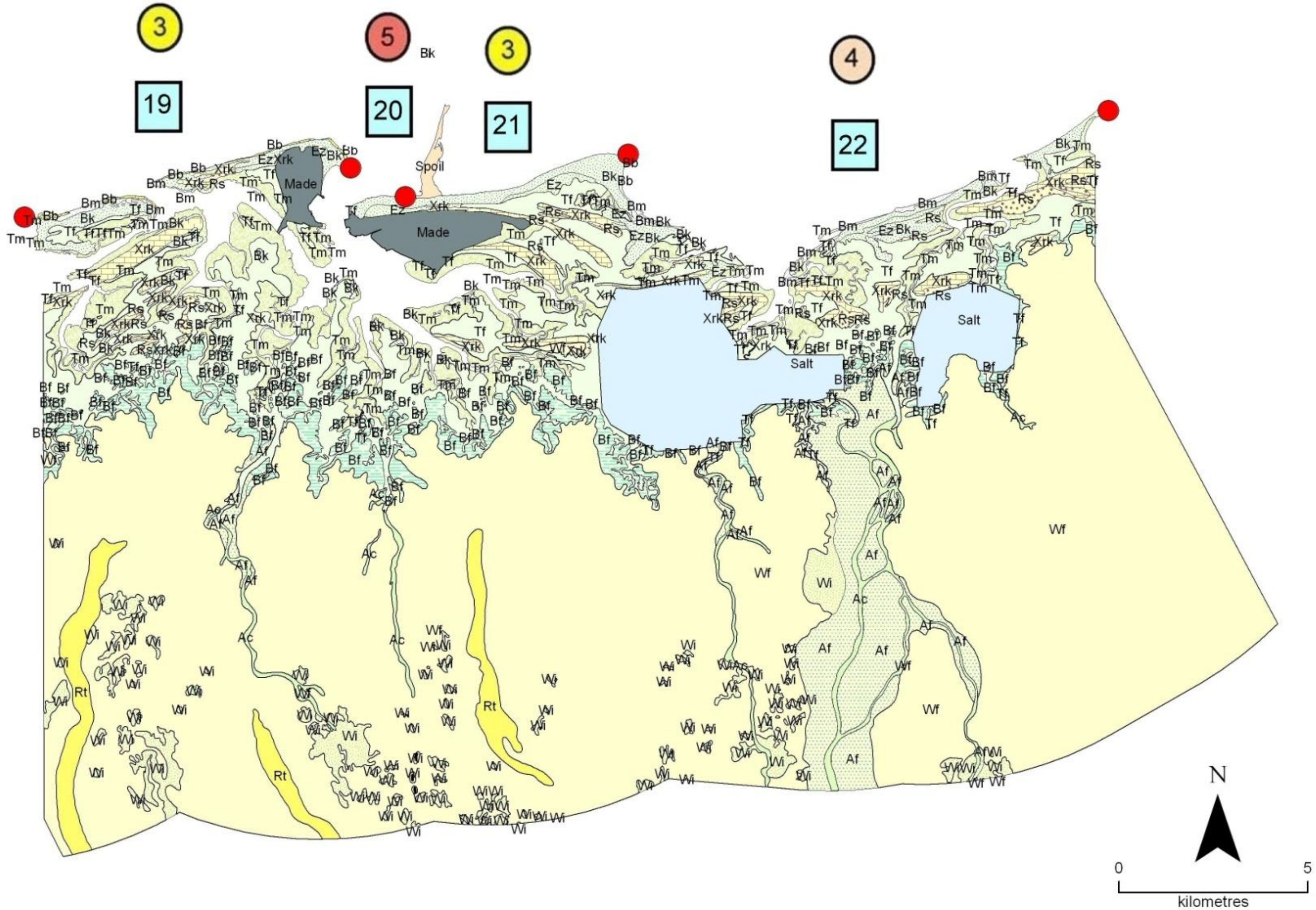



**Figure 2-3: Landforms and Sediment Cells for Port Hedland Area of Planning Interest**
**Landform Maps for all Areas of Planning Interest are in Section 6.**

Within each landform association the rank of individual land systems 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 incorporating them currently have a low level of instability. Conversely a high rank (5) indicates the structure is likely to change or cause change over a planning horizon of 100 years, and that the landforms present are currently unstable. Rationale for the ranking is discussed below and in Section 3.4. The criteria used to rank susceptibility and instability of land systems and landforms of the Pilbara coast are listed in Table 2-7.

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

## 2.4. SUSCEPTIBILITY AND INSTABILITY

Susceptibility and instability are related concepts drawn from geological and 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 ten land systems and landform units. Key references considered in the evaluation of susceptibility and instability includes:

1. Cliffs: Trenhaile (1987); Sunamara (1992); Woodroffe (2003).
2. Coral Reefs: Woodroffe (2003); Collins & Twiggs (2011).
3. Tidal flats and sub-tidal terraces: Brown (1988); Semeniuk (1996a); Dyer *et al.* (2000); Woodroffe (2003); Morton & Holmes (2009); Davies & Woodroffe (2010); Perillo & Piccolo (2011).
4. Deltas, estuaries and rivers: Wright (1985); Perillo (1995); Brearley & Hodgkin (2005).
5. Coastal plains and outwash plains: Wright (1985); Woodroffe & Mulrennan (1993); Woodroffe *et al.* (1989); Semeniuk (1996); Cobb *et al.* (2007).
6. Cuspate forelands & Tombolos: Zenkovich (1967); Sanderson & Eliot (1996); Sanderson (2000).
7. Barriers: Chapman *et al.* (1982); Cowell & Thom (1994); Roy *et al.* (1994); Hesp & Short (1999a); Masetti *et al*. (2008).
8. Beaches: Nordstrom (1980, 1992); Wright & Short (1984); Jackson *et al.* (2002); Short (2005); Eliot *et al.* (2006); Green (2008); Doucette (2009).
9. Coastal Dunes: Hesp & Short (1999a, b); Hesp (2002); Houser & Matthew (2011).

**Table 2-7: Criteria for Landform Susceptibility and Stability in the Pilbara**

**(A) SUSCEPTIBILITY (Potential for structural impacts)**

| INNER SHELF MORPHOLOGY (Depth: 20m) | Rank |
|---|---|
| Archipelago OR<br>Remnant barrier chain sheltering the coast OR<br>Both low waves (wide >40km) & surge (effective narrow <12km) | 1 |
| Moderate waves (moderate 25-40km) & low surge (effective narrow <12km) OR<br>Low waves (wide >40km) & moderate surge (effective moderate 12-25km) | 2 |
| Both moderate waves (moderate 25-40km) & surge (effective moderate 12-25km) | 3 |
| High waves (narrow <25km) & low surge (effective narrow <12km) OR<br>Low waves (wide >40km) & high surge (effective wide >25km) | 4 |
| High waves (narrow <25km) & moderate or high surge (effective >12km) OR<br>High surge (effective wide >25km) & moderate or high waves (<40km) | 5 |

| SUBTIDAL SHOREFACE STRUCTURE (Depth <20m) & COASTAL ORIENTATION | Rank |
|---|---|
| Bare rock as reefs and/or pavements | 1 |
| Reef, pavement and bare sediments OR<br>Extensive (>50%) reef & gravel patches | 2 |
| Intertidal/subtidal terrace with few tidal channels OR<br>Patch reef, pavement & bare sediment | 3 |
| Intertidal/subtidal terrace with many tidal channels OR<br>Shallow embayment facing NW-NE | 4 |
| Planar shoreface (no rock) OR<br>Gulf or deep embayment facing NE | 5 |

| INTERTIDAL SHORE | Rank |
|---|---|
| Cliff plunging to subtidal level OR<br>Continuous bluffs, rocky coast or platform HWST | 1 |
| Cliff and intertidal platform OR<br>Continuous intertidal platform with perched beach | 2 |
| Non-cliffed, gently sloping rocky coast OR<br>Near continuous intertidal platform, ramp and perched beach | 3 |
| Beach rock and unconsolidated sediment OR<br>Discontinuous intertidal platform | 4 |
| Intermittent rock outcrops , including storm ridges with lithified cores OR<br>Unconsolidated sediments (eg sand) | 5 |

| ONSHORE STRUCTURES INCLUDING BARRIERS & DELTAS | Rank |
|---|---|
| High rocky coast (>5m above high tide) | 1 |
| Episodic transgressive barrier OR<br>Prograded barrier OR<br>Wide (>100m) foredune plain | 2 |
| Stationary barrier OR<br>Receded barrier OR<br>Wide (>50m) spits and cheniers | 3 |
| Outwash plains OR<br>Deltaic plains OR<br>Mainland beach | 4 |
| Active delta OR<br>Inherited basins OR<br>Narrow (<50m) spits and cheniers | 5 |

**(B) INSTABILITY (Current changes to land surface)**

| INSHORE SUBSTRATE (Depth <5m) | Rank |
|---|---|
| Hard rock (eg Granite) OR<br>Greater than 75% reef or pavement | 1 |
| Moderately hard rock (eg Sandstone) OR<br>50 to 75% reef or pavement | 2 |
| Moderately soft rock (eg Limestone) OR<br>25 to 50% reef or pavement | 3 |
| Soft rock (eg Eolianite or calcarenite) OR<br>Less than 25% reef or pavement | 4 |
| Bare sediment surface: No rock outcrop | 5 |

| RIVERS & TIDAL CREEKS (No/10km shore) | Rank |
|---|---|
| No rivers OR<br>Small, coastal catchment OR<br>Nearly continuous rocky shore | 1 |
| River mouth connected to basin (indirectly related to tidal creek) OR<br>Small to moderate coastal catchment OR<br>Nearly continuous sandy shore | 2 |
| Tidally dominated river delta with open mouth (funnel shape) OR<br>Moderate sized inland catchment OR<br>Shoreline with 1 or 2 tidal creeks per 10km | 3 |
| River mouth directly connected to tidal creek OR<br>Moderate to large river catchment OR<br>3 or 4 tidal creeks per 10km shoreline | 4 |
| River dominated delta OR<br>Large river catchment OR<br>Irregular shoreline with >5 tidal creeks per 10km shoreline | 5 |

| FRONTAL DUNE COMPLEX OR TIDAL FLATS (Shoreline features) | Rank |
|---|---|
| High (>15m), wide (>150m) frontal dunes OR<br>Rocky topography OR<br>Continuous lithified chenier ridge | 1 |
| Moderately high (10-15m), wide (>150m) frontal dunes OR<br>High (>15m), moderately wide (50-150m) frontal dunes OR<br>Vegetated tidal flat margin with few tidal creeks | 2 |
| Low (<10m), wide (>150m) frontal dunes OR<br>Moderately high (10-15m), moderately wide (50-150m) frontal dunes OR<br>High (>15m), narrow (>150m) frontal dunes OR<br>Vegetated tidal margin with many tidal creeks | 3 |
| Low (<10m), moderately wide (50-150m) frontal dunes OR<br>Moderately high (10-15m); narrow (<50m) frontal dunes OR<br>Discontinuous chenier ridge OR<br>Moderately high (>5m) storm bar | 4 |
| Low (<10m), narrow (<50m) frontal dunes OR<br>Salt marsh OR<br>Tidal flats with surface run-off / tidal channels OR<br>Low (<5m) storm bar | 5 |

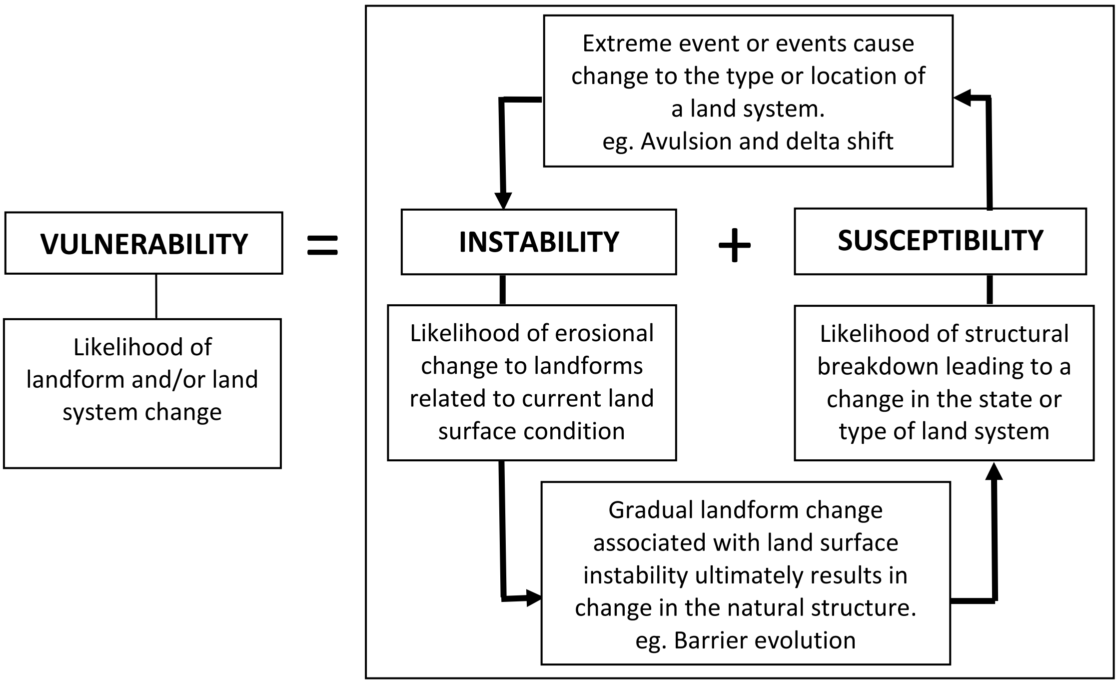
| HINTERLAND TOPOGRAPHY OR MUDFLATS (Landward Features of the Surge Zone) | Rank |
|---|---|
| Rocky topography OR<br>Narrow supratidal mudflats | 1 |
| Rock outcrops and alluvial flats OR<br>Broad supratidal mudflats & few tidal creeks | 2 |
| Coastal dune fields OR<br>Broad supratidal mudflats & common tidal creeks | 3 |
| Longitudinal dunes on floodplains OR<br>Broad bare supratidal mudflats, palaeochannels & tidal creeks | 4 |
| Outwash plain, floodplain OR<br>Broad bare supratidal mudflats with residual mounds, palaeochannels & tidal creeks | 5 |

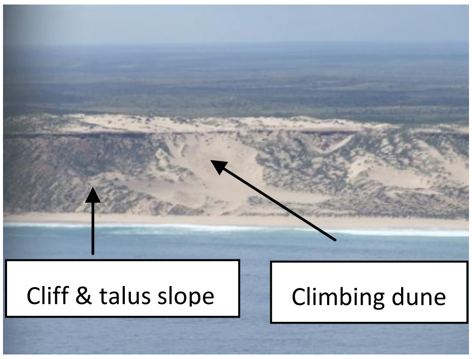
References such as those by Semeniuk (1996) describing land systems on the Western Australian coast and Hsu *et al.* (2008) describing topographic control of the shoreline geometry have been used where appropriate and available. However there are gaps in knowledge, particularly with respect to mixed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

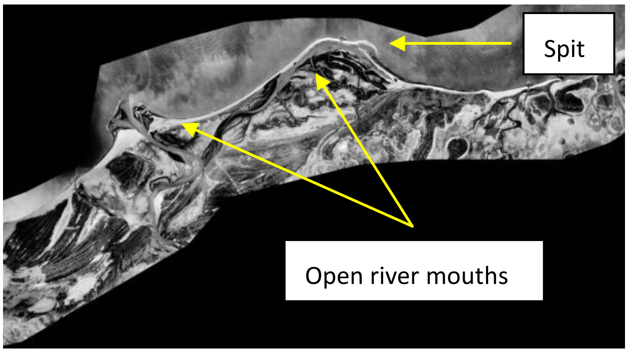
Together, the concepts of susceptibility and instability describe the *vulnerability* of coastal land systems and landforms to metocean change (Figure 2-4). Briefly, if current landform change is continued for long enough, exacerbated by natural changes in climate, or an extreme event occurs the land 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.

Viewing metocean change and landform responses at a particular scale is a matter of convenience. In reality, the environment is dynamic at all scales with slower changes providing a long-term context for faster ones (Figure 2-6). 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* *whole cell* at that scale relative to others in a series described for a region or administrative coastal area.

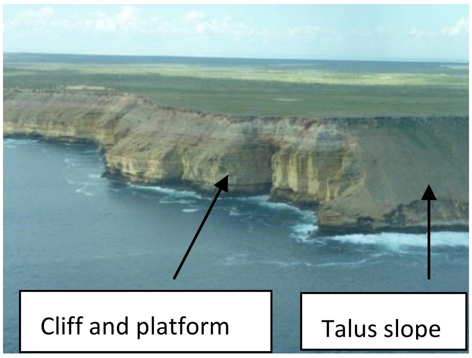


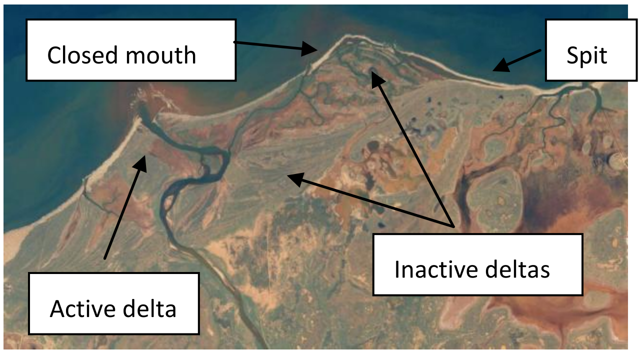




Above: Perched barrier and climbing dunes
Below: No barrier. Perched beach and old dunes

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




Incremental change: Gradual sediment loss from accretionary landforms such as beaches and foredune plains adjoining cliffs results in change 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**

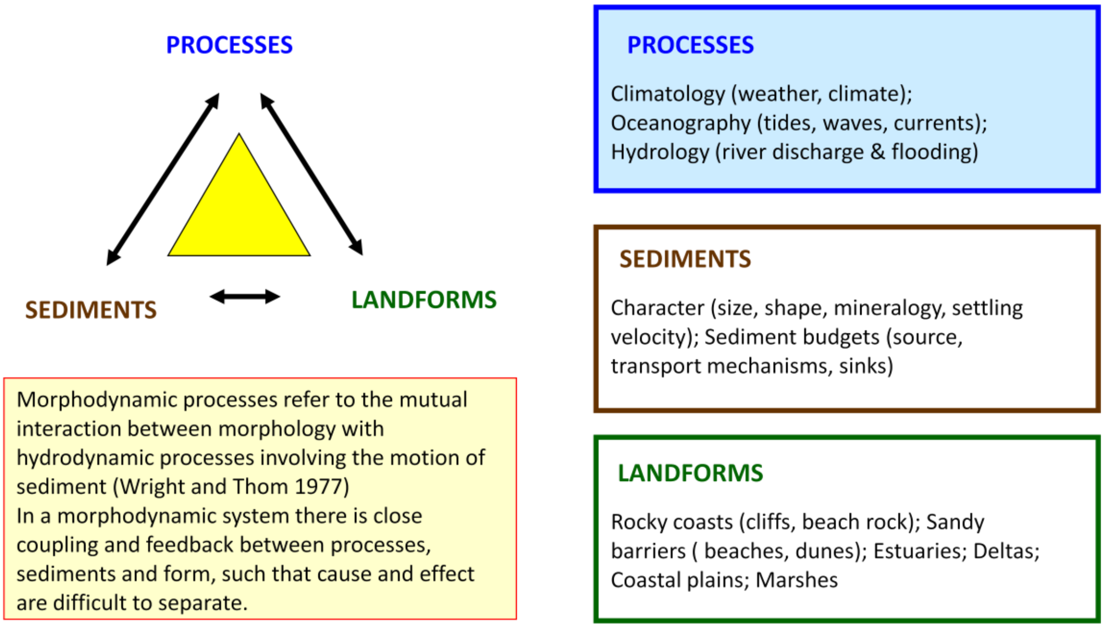



**Figure 2-5: Components of a Morphodynamic System on a Sandy Coast**

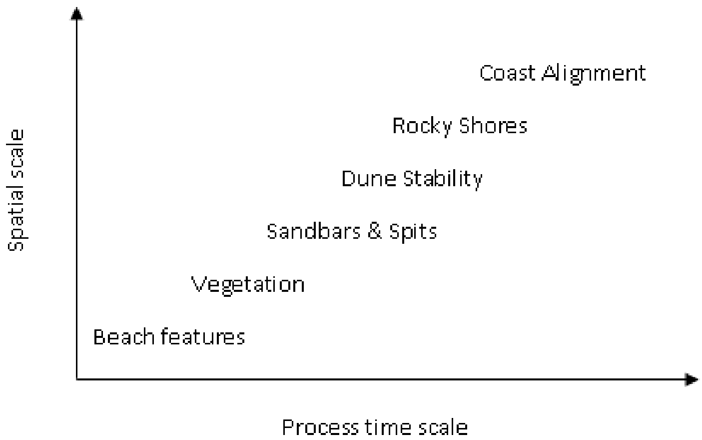



**Figure 2-6: Scales of Coastal Change for Different Coastal Features**

### 2.4.1. Land System Susceptibility

Estimation of the susceptibility of land systems to large-scale change in the natural structure is based on published descriptions of coastal evolution over the past 6,000 years; however the focus of the report is on large scale landform changes likely to occur over a planning horizon of 100 years. Some of these features are illustrated in Figure 2-7 to Figure 2-12. Over geologic time deposition by rivers in the region has formed substantial tracts of low-lying floodplain between higher rocky outcrops. As a result the unconsolidated sediments of the Pilbara coast commonly comprise riverine plains, relict deltas and active deltas (Semeniuk 1996) with a veneer of marine sediments forming barrier dunes, cheniers and spits close to shore. The riverine land-systems support landforms characteristic of their depositional environments; palaeochannels indicative of switching flow paths, pools in abandoned channels and overbank basins (Damara WA 2010a). Close to the shore they commonly carry evidence of the rise and fall of sea level over millennia as well as evidence of river floods and marine inundation that has occurred since relative stabilisation of sea level approximately 6000 years ago. The coastal margins of the riverine plains, relict deltas and active deltas have been modified by tidal inundation, storm surge and flood runoff to form tidal flats, chenier storm ridges, beaches and subtidal terraces, all of which are affected by stream flow and tidal channels. The susceptibility of land systems in a coastal compartment or sediment cell to large scale change is dependent on the inherited resilience of its landforms; the area of rocky coast, degree of lithification of partly unconsolidated sedimentary landforms and the degree to which pre-Holocene landforms have been affected by previous high sea level conditions.

### 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 2-13 to Figure 2-19.

In the context of this report landform instability is apparent as changes to the landform pattern as the landforms comprising a land system develop and are rearranged or obliterated. These changes are associated with short to medium term variation in weather and occur in response to fluctuation sea level as well as to the intensity of marine and riverine processes. They are manifest as variation in the availability of unconsolidated sediment in the inshore waters; shoreline migration; alteration of the geometry of perched beaches; formation or destruction of spits, cheniers, foredunes and frontal dunes; expansion, contraction, opening and closure of tidal creek networks; infill or scouring of mudflats and mudflat basins; and terrestrial migration of stream and riverchannels, including avulsion and reactivation of palaeochannels.

Extensive, low lying riverine plains, relict deltas and active deltas are dominating features of the coastal margin n the Pilbara. They are frequently modified by tidal inundation, storm surge and flood runoff. Marine inundation by tides, storm surge frequently interacts with river flooding and extends kilometres landward. It is extent is apparent as high level wrack lines deposited well above the level of present day tides. Although these have yet to be systematically mapped they potentially provide an indication of the areas most affected as well as the elevation and date at which inundation occurred.

Tidal creeks and, intermittently in the Pilbara, the major rivers provide the basic circulatory systems through which water, sediments, organic matter, nutrients and pollutants are transported in and out of the mudflat wetlands thus effecting exchange with the open ocean. Perillo (2009) points out that as a mudflat *evolves in time and space, tidal creeks follow up and, many times, set the pace of this evolution since they, being the most energetic environment, are most sensitive to possible changes on the external variables that influence the systems. In fact, tidal creeks are one of the first features that appear upon the formation of a coastal wetland either by modification of earlier fluvial networks or by the direct action of the tides, groundwater and precipitation*. Hence the presence of tidal creeks, their connection to streams and rivers, and their subtidal extension across tidal flats are significant indicators of the relative stability of different coastal compartments and sediment cells.In the Pilbara the form of tidal creeks networks ranges from runoff drainage streams cut by flood waters and temporarily maintained by tidal flows after flood run off to permanent streams driven by tidal and other fluctuations in sea level. They also vary from isolated channels draining a wetland basin to complex networks directly connented to streams and rivers. The disparate types of tidal creek system affect coastal stability in different ways and to different degrees.

A range of fluvial affects on coastal stability is acknowledged in the criteria used to determine coastal stability. The emphemeral streams and rivers of the Pilbara region vary significantly in their coastal impacts. All are subject to intermittent flooding and, unless dammed, contribute to floodplain development along the coast. However, not all carry sediment to the shore. Many of the smaller streams debouche into overbank basins inherited from a more active period of floodplain development or from pre-Holocene higher sea level conditions when coastal lagoons were established. Their potential for destabilising the shore is limited to indirect action by basin flooding and increased runoff through tidal creeks draining the basins. In contrast to this the larger rivers discharge directly into the ocean. Maximum discharge is irregular and intermittent, and may ovccur after prologed phases of low discharge, as has been observed in the Ashburton River. Large rivers, such as the Ashburton and De Grey, have a direct influence on coastal stability, particularly though the intermittent supply of sediment to the coast and through channel switching (avulsion) when the main channel relocated on the delta it is building.

Sediment from tidal creeks and rivers, together with that from biological sources, reworking following erosion of existing deposits and from the inner continental shelf may be deposited at the shore in the form of beaches, cheniers, spits and dunes. The type of landform developed and its ultimate stability depends on abundance of sediment available for development, processes leading to deposition and the locale in which it developed. All the unconsolidated landforms listed above commonly overlie or abut sections of rocky coast including beachrock, platforms and irregular rocky terrain or have been driven landward across inherited riverine plains with the Holocene rise in sea level. The relative stability of each is a function of the volume of sediment and the height of the surface on which it has developed as well as its sedimentary characteristics and processe affecting it.

Although not well developed along the Pilbara coast, the association of landforms comprising dune barriers, particularly their geographic extent provides an indication of sediment availability. For example, Roy *et al*. (1994) attributed the type of barrier found on wave dominated coast to variation in continental shelf gradient and sand supply as well as the wave regime. The types they identified ranged from (a) sediment poor areas of eroding coast where there was a continuing loss of sand onto a steep continental shelf to (b) transgressive dune barriers and a large sand supply from a low-gradient continental shelf. With notable variation due to the role of rivers and inherited basins their models are applicable to parts of the Pilbara coast. Barrier types vary along the Pilbara coast, ranging from the extensive prograded and episodic transgressive systems between Turbridgi and Beadon Creek, through receded barrier systems along the Gnoorea coast between Forty

Mile Beach and Pelican Point to mainland barriers or no barriers on the exposed rocky coast between. 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.

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 2-11) which he related to shoreface processes. His observations, with those of Short (1999) are built on an understanding of the interaction of inshore, beach and dune processes, in which short-term variation in coastal stability is both affected by and affects the long-term evolution of the coast.

**Rank 1:** Bare rock

**Rank 2:** Extensive reef & pavement

**Rank 3:** Intertidal & subtidal terrace; few channels

**Rank 4:** Intertidal & subtidal terrace; many channels

**Rank 5:** Planar shoreface (no rock)

**SUBTIDAL SHOREFACE MORPHOLOGY 1**

The *susceptibility* of coastal land refers to the intrinsic propensity of a coastal land system or landform *structure* to alter in response to projected change in metocean conditions over a long period, commonly extending to millennia.

Variation in structure may occur spatially, due to differences in rock type; or temporally as a result in the differences in the strength of the same rock type and exposure to disparate processes.

**SUSCEPTIBILITY**

**Figure 2-7: Susceptibility in the Intertidal Shoreface: Subtidal Shoreface**
**The sequences illustrated identify elements of subtidal shoreface morphology likely to affect shoreline interaction with metocean processes**

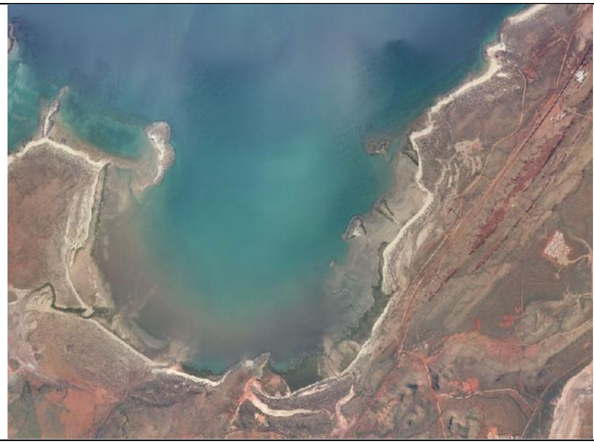
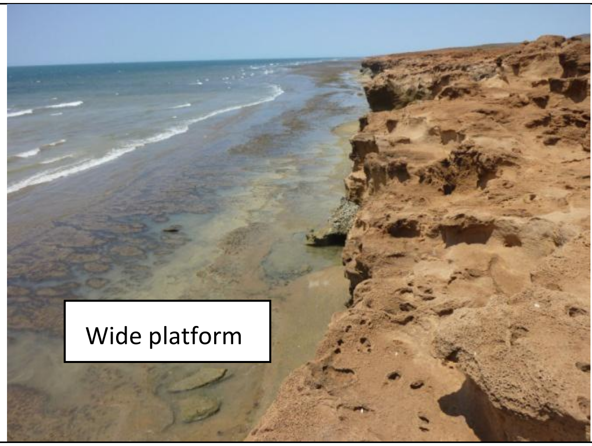
| | | |
|---|---|---|
|  |  |  |
| **Rank 1:** Bare rock (Here a 500m wide coral platform) | **Rank 2:** Extensive reef & pavement (>50% rock) | **Rank 3:** Patch reef, pavement & bare sediment (bars) |
|  |  | **SUB-TIDAL SHOREFACE MORPHOLOGY & PLAN SHAPE OF THE SHORELINE**<br>The *susceptibility* of coastal land refers to the intrinsic propensity of a coastal land system or landform *structure* to alter in response to projected change in metocean conditions over a long period, commonly extending to millennia.<br>Variation in structure may occur spatially, due to differences in rock type; or temporally as a result in the differences in the strength of the same rock type and exposure to disparate processes. |
| **Rank 4:** Shallow embayment facing NW to N. | **Rank 5:** Gulf or deep embayment facing NE | **SUSCEPTIBILITY** |

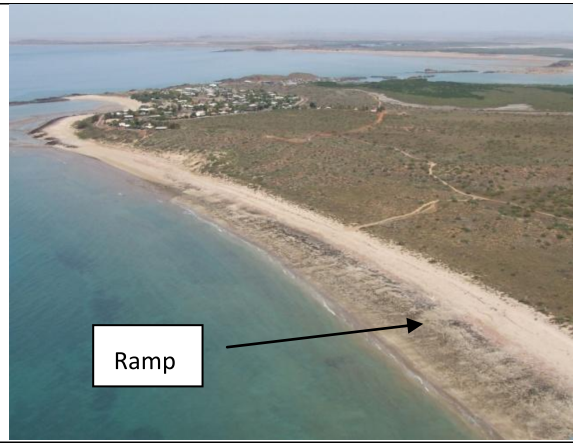
**Figure 2-8: Susceptibility in the Intertidal Shoreface: Shoreface and Plan Shape**

**The sequences illustrated identify elements of subtidal shoreface morphology likely to affect shoreline interaction with metocean processes**

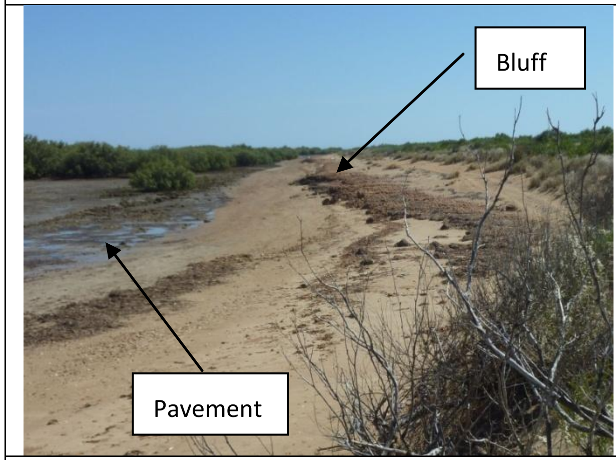

**Rank 1:** High cliff or talus slope (>10m) plunging to subtidal level




**Rank 2:** Moderate to high cliff (5 – 10m) or talus slope with an intertidal platform or ramp




**Rank 3:** Gently sloping rocky shore. (Shown is a wide beachrock ramp grading to pavement)




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

**Rank 5:** Intermittent rock outcrops alternating with sandy beach

**ROCKY INTERTIDAL SHORE**

The *susceptibility* of coastal land refers to the intrinsic propensity of a coastal land system or landform *structure* to alter in response to projected change in metocean conditions over a long period, commonly extending to millennia.

Variation in structure may occur spatially, due to differences in rock type; or temporally as a result in the differences in the strength of the same rock type and exposure to disparate processes.

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

**SUSCEPTIBILITY**

**Figure 2-9: Susceptibility at the Shore: Rocky Intertidal Shore**

| | | |
|---|---|---|
|  |  |  |
| **Rank 1:** Continuous bluffs, rocky coast or platform above high water spring tide | **Rank 2:** Continuous intertidal platform with perched beach | **Rank 3:** Near continuous rock platform or beachrock ramp and perched beach |
|  |  | **MIXED SANDY AND ROCKY SHORE**<br>The *susceptibility* of coastal land refers to the intrinsic propensity of a coastal land system or landform *structure* to alter in response to projected change in metocean conditions over a long period, commonly extending to millennia.<br>Variation in structure may occur spatially, due to differences in rock type; or temporally as a result in the differences in the strength of the same rock type and exposure to disparate processes.<br>The sequence illustrated here loosely follows that described by Sunamara (1992). |
| **Rank 4:** Discontinuous intertidal platform | **Rank 5:** Unconsolidated sediments | **SUSCEPTIBILITY** |

**Figure 2-10: Susceptibility at the Shore: Mixed Sandy and Rocky Shore**

**Rank 1:** High rocky coast (Depuch Island)

**Rank 2:** Episodic transgressive or prograded barrier

**Rank 3:** Stationary or receded barrier

**Rank 4:** Mainland beach or high (>5m) storm bar

**Rank 5:** Low (<5m) storm bar and washover fans

**ONSHORE STRUCTURES**

The *susceptibility* of coastal land refers to the intrinsic propensity of a coastal land system or landform *structure* to alter in response to projected change in metocean conditions over a long period, commonly extending to millennia.

Variation in structure may occur spatially, due to differences in rock type; or temporally as a result in the differences in the strength of the same rock type and exposure to disparate processes.

**SUSCEPTIBILITY**

**Figure 2-11: Susceptibility of Onshore Structures: Barriers**

**Rank 1:** High rocky coast (perched dune on high platform)

**Rank 2:** Wide (>100m) foredune or chenier plain (Spit, cheniers & mudflats at mouth of Ashburton R.)

**Rank 3:** Wide (>50m) spits and cheniers **(**Spits flanking Cape Thouin)

**Rank 4:** Outwash or deltaic plain

**Rank 5:** Active delta or inherited basin (Fortescue River mouth)

**ONSHORE STRUCTURES: CHENIERS & DELTAS**

The *susceptibility* of coastal land refers to the intrinsic propensity of a coastal land system or landform *structure* to alter in response to projected change in metocean conditions over a long period, commonly extending to millennia.

Variation in structure may occur spatially, due to differences in rock type; or temporally as a result in the differences in the strength of the same rock type and exposure to disparate processes.

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

**SUSCEPTIBILITY**

**Figure 2-12: Susceptibility of Onshore Structures: Cheniers & Deltas**

| | | |
|---|---|---|
|  |  |  |
| **Rank 1:** Greater than 75% reef or pavement | **Rank 2:** 50 to 75% reef or pavement | **Rank 3:** 25 to 50% reef or pavement |
|  |  | **INSHORE SUBSTRATE**<br>**PROPORTION OF BARE SAND INSHORE**<br>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,<br>Instability is estimated as the proportion of bare sand to rock iin the inshore waters, with the exposure likely to vary with changing sediment supply and coastal process intensity. |
| **Rank 4:** Less than 25% reef or pavement | **Rank 5:** Bare sediment surface: No rock outcrop | **INSTABILITY** |

**Figure 2-13: Instability of the Inshore: Rock Exposed as Reef or Seabed Pavement**

| | | |
|---|---|---|
|  |  |  |
| **Rank 1:** No rivers or small coastal catchments | **Rank 2:** River discharges onto mudflat basin and is indirectly connected to a tidal creek; small to moderately sized catchments | **Rank 3:** River or stream intermittently linked to tidal creek in a mudflat basin; moderately sized catchments |
|  |  | **RIVER CONNECTIVITY TO SHORE**<br>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. |
| **Rank 4:** River channel or stream merges with tidal creek; moderate to large sized catchment | **Rank 5:** River or stream has a delta with a single large channel or distributaries discharging directly into the ocean; large river catchment | **INSTABILITY** |

**Figure 2-14: Instability: River Connectivity to the Shore**

**Rank 1:** Mainly continuous rocky shore. No tidal creeks

**Rank 2:** Mainly continuous sandy beach. No tidal creeks

**Rank 3:** One or two tidal creeks per 10km of shoreline

**Rank 4:** Three or four tidal creeks per 10km of shoreline

**Rank 5:** Irregular shoreline with 5 or more than tidal creeks per 10 km of shoreline

**TIDAL CREEK CONNECTIVITY TO SHORE**

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.

Tidal creek connectivity between terrestrial environments and the ocean has been estimated as the number of streams crossing the length of coast under consideration.

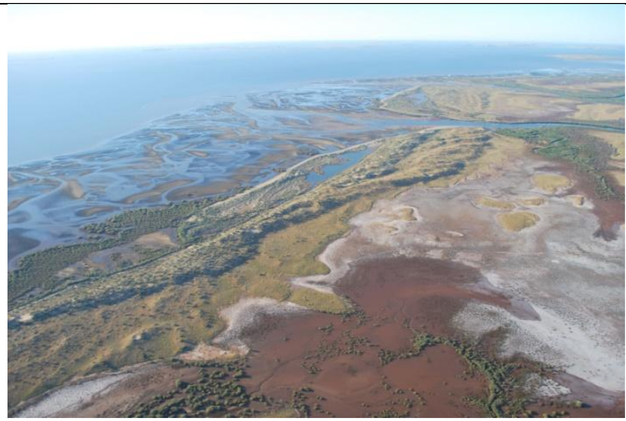
**INSTABILITY**

**Figure 2-15: Instability: Tidal Creek Connectivity from Ocean to Terrestrial Environment**

| | | |
|---|---|---|
|  |  |  |
| **Rank 1:** High (>15m), wide (>150m) frontal dunes | **Rank 2:** Moderately high (10-15m), wide (>150m) frontal dunes OR High (>15m), moderately wide (50-150m) frontal dunes | **Rank 3:** Low (<10m), wide (>150m) frontal dunes OR Moderately high (10-15m), moderately wide (50-150m) frontal dunes |
|  |  | **FRONTAL DUNE COMPLEX**<br>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.<br>Height and width of the dune field indicates the likelihood of the dunes being overwhelmed by extremely high sea level .events. |
| **Rank 4:** Low (<10m), moderately wide (50-150m) frontal dunes OR Moderately high (10-15m), narrow (<50m) frontal dunes | **Rank 5:** Low (<10m), narrow (<50m) frontal dunes | **INSTABILITY** |

**Figure 2-16: Instability: Frontal Dune Complex**

**Rank 1:** Nearly continuous lithified chenier ridge separates mudflats from shore



**Rank 2:** Vegetated tidal flat margin with cheniers and few tidal creeks

**Rank 3:** Vegetated tidal flat margin with many tidal creeks

**Rank 4:** Discontinuous chenier ridge or moderately high storm bar (<5m)

**Rank 5:** Tidal flats merging with intertidal terrace or high storm bar (>5m)

**TIDAL FLATS**

**Mean Sea Level to High Water Spring Tide**

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.

**INSTABILITY**

**Figure 2-17: Instability: Tidal Flats between Mean and Spring High Tide**

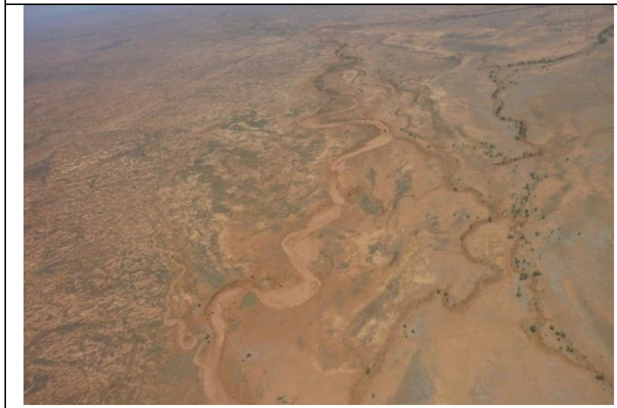
| | | |
|---|---|---|
|  |  |  |
| **Rank 1:** Rocky terrain | **Rank 2:** Rock outcrops and alluvial flats | **Rank 3:** Coastal dune fields (Barriers) |
|  |  | **HINTERLAND TOPOGRAPHY**<br>**Landward of High Water Spring Tide Level**<br>Landform *instability r*efers to the current condition of the 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. |
| **Rank 4:** Floodplains, may support longitudinal dunes; palaeochannels, braided streams, meanders & billabongs (pools) may be present, | **Rank 5:** Seaward edge of outwash plains & floodplains merging with mudflats; palaeochannels and overbank basins present | **INSTABILITY** |

**Figure 2-18: Instability of the Hinterland Topography: Landward of Spring High Tide**

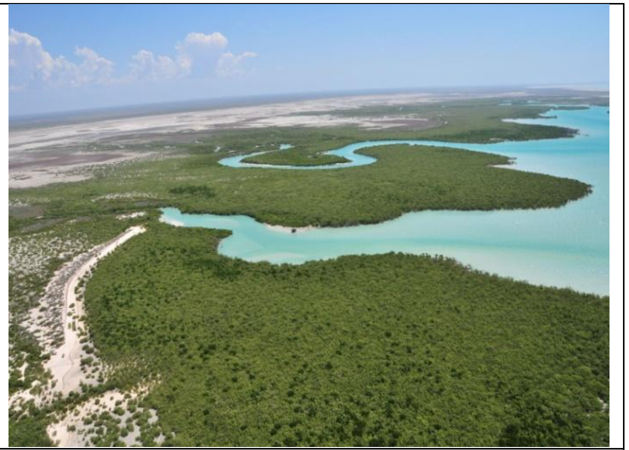
| | | |
|---|---|---|
|  |  |  |
| **Rank 1:** Narrow tidal flats | **Rank 2:** Broad mudflats with few tidal creeks | **Rank 3:** Broad mudflats & common tidal creeks |
|  |  | **HINTERLAND TOPOGRAPHY**<br>**Tidal Flats above High Water Spring Tide Level**<br>Landform *instability r*efers to the current 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. |
| **Rank 4:** Broad bare salt flats with Halophytic patches, palaeochannels & tidal creeks | **Rank 5:** Broad bare salt flats with numerous residual mounds, palaeochannels & large tidal creeks | **INSTABILITY** |

**Figure 2-19: Instability of the Hinterland Topography: Tidal Flats above Spring High Tide**

## 2.5. ESTIMATION OF VULNERABILITY

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

Step 1: Landform descriptions incorporating the criteria used to separately describe the susceptibility and instability of a tertiary compartment or tertiary cell were compiled for the inshore, beachface and backshore, as well as the shoreline. An example for a tertiary compartment in the Port Hedland area is provided in Table 2-8. Descriptions of landforms for each of the tertiary compartments along the Pilbara coast are in Appendix E.

Step 2: A five point ranking was determined for each of the criteria used (Table 2-7);

Step 3: The rank scores for the susceptibility and instability criteria were separately ordered into four zones (Table 2-9) and summed for each planning unit;

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

Step 5: The likelihood ranks were then combined to identify the indicative or relative vulnerability of each planning unit (Table 2-10). The steps used to combine the ranks are described in Section 2.6.

**Table 2-8: Landform Descriptions for an Example Tertiary Compartment in Port Hedland The descriptions are intended to facilitate determination of the susceptibility and instability rankings from Table 2-10**

| TERTIARY COMP. | INNER-SHELF MORPHOLOGY | SUBTIDAL SHOREFACE | INTERTIDAL SHORE | BACKSHORE LANDFORMS |
|---|---|---|---|---|
| Downes Island to Beebingarra Creek | The inner-shelf is wide. Water depth is <10m approximately 14km from shore; and 20m approximately 47km from shore. Three islands are located in State Waters. | Water depth is <5m for approximately 8km from shore. The inshore waters include tidal channels, subtidal reef platforms and rock outcrops. Sandy tidal flats are 3.5km wide in the east. The Spoil Bank is a major source of sediment to the subtidal shoreface. | The shore is markedly dissected with a lithified chenier ridge and tidal flats between the ridges. Tidal flats are 3.5km wide in the east. There are approximately five tidal creeks per 10km along the irregular shore. Finucane Island has a calcarenite rock platform and low cliffs along its northern shore, with mangroves in the sheltered southwest shore. Port Hedland to Cooke Point has a sandy beach overlying beachrock and tempestites abutting Pleistocene dunes. The Spoil Bank is a major source of sediment to the coast, but also causes localised erosion. | Tidal creeks and mudflats occur between an outwash plain drained by small creeks to landward and chenier ridges, some of which are lithified. Three streams (Beebingarra, Petermarer and Tabba Tabba Creeks) and the Turner River drain onto mudflats and intermittently connect with tidal creeks. |

**Table 2-9: Coastal Zones Used for Ranking of Susceptibility and Instability**

| | SUSCEPTIBILITY | INSTABILITY |
|---|---|---|
| 1 | Inner Shelf Morphology | Inshore Substrate |
| 2 | Subtidal Shoreface Structure | Rivers or Tidal Creeks |
| 3 | Intertidal Shroe | Frontal Dune Complex or Tidal Flats (Shoreline) |
| 4 | Onshore Structures | Hinterland Topography or Tidal Flats |

**Table 2-10: Port Hedland Tertiary Cell Susceptibility, Instability and Vulnerability Ranking A similar table is used to compile rankings for individual compartments**

| Tertiary Compartment | Inner Shelf Morphology | Subtidal Shoreface Structure | Intertidal Shore | Onshore Structures | Susceptibility Score | Susceptibility Ranking | Inshore Substrate | Rivers or Tidal Creeks | Frontal Dune Complex or Tidal Flats | Hinterland Topography or Tidal Flats | Instability Score | Instability Ranking | MATRIX SCORE | Vulnerability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Beebingarra Creek to Wattle Well | 2 | 4 | 5 | 5 | 16 | H | 4 | 4 | 4 | 5 | 17 | H | 5 | H |
| Downes Island to Beebingarra Creek | 3 | 2 | 4 | 5 | 14 | M | 4 | 2 | 2 | 5 | 13 | M | 3 | M |
| West Turner River to Downes Island | 3 | 3 | 4 | 5 | 15 | H | 4 | 3 | 4 | 5 | 16 | H | 5 | H |

## 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 its natural structural integrity based on the developmental state of similar 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 2-11a.
- 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 2-11b.
- 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 2-20). In turn the vulnerability rankings derived from the matrix have been interpreted as a combination of those for susceptibility and instability (Table 2-12).

Under the State Coastal Planning Policy (WAPC 2013) 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 2-12 in which constraints indicated by the likelihood of coastal change are identified and the implications of vulnerability rankings for coastal management indicated.

**Table 2-11: Implications for Coastal Management**

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

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

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

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

Separating susceptibility and instability is a device to qualitatively examine overall coastal stability, herein defined for the purposes of the report as vulnerability. As they are applied in the report, the twin concepts identify disparate aspects of stability, both of which should be considered in coastal planning and management. Hence, the susceptibility of a geomorphic structure to change and its present instability condition should not be used separately in risk assessment. The various combinations of susceptibility and instability rankings to yield the five vulnerability ranks are listed in Table 2-13 together with their implications for coastal management and the degree of risk represented by each level of vulnerability.

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

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

**Figure 2-20: Indicative Vulnerability Matrix for a Mixed Sand and Rock Coast with Dunes Based on Combined Estimates of Risk for Susceptibility and Instability**

**Table 2-12: 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 2-13: Combining the Coastal Rankings and Implications for Coastal Management

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

# 3. Regional Context: Land Systems and Landforms

The hierarchy of compartments used to identify the planning units generally accords with the terrestrial land systems described by van Gool *et al.* (2005) for soils in the agricultural areas of Western Australia. In this report, provinces are approximately equivalent to WA coastal regions; zones to primary compartments; land systems to tertiary and secondary compartments; landform to tertiary compartments and sediment cells; and landform elements to sediment cells (Figure 3-1). At each scale an individual compartment has an association of landforms and processes that distinguishes it from its neighbouring compartments. However, within each of the five 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 compartment scale, with tertiary compartments being examined here. Conversely, the condition or stability of landforms is most relevant to investigation of tertiary compartments and sediment cells, the latter of which have been used in the examination of Areas of Planning Interest.

In both contexts, an objective of this report is to indicate the principal geologic, geomorphic and metocean factors contributing to the relative vulnerability of sediment cells along the coast and further develop the applications listed in Table 2-5 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 2-7).

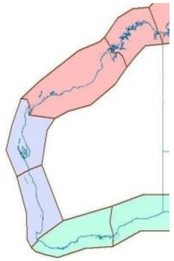
At a broad provincial scale the Study Area, extending from Hope Point to Tryon Point, falls mainly within the North Western Coasts Province of the West Coast Division. It encompasses part of the Exmouth region, all of the Pilbara region proper and the Eighty Mile Beach sector of the Canning region (Figure 3-2).

Climatologically, the province is in an arid l zone between the Temperate and Tropical Coast Regions. The Study Area is affected by a variety of weather systems commonly including the northen components of anticyclonic high pressure systems that merge with the prevailing SE trade wind s, seabreezes and the seasonally dominant tropical cyclones (Section 4.2.1). Peak frequencies of tropical cyclones are recorded in the Pilbara between Karratha and Onslow, but are common in the summer months (December to March) throughout the region (Damara WA 2008, 2009).

**1**

**Zones:** Broad sectors of the Australian continent based on climate

**2**

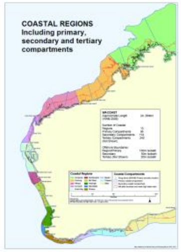


**Divisions:** Provides an overview of the whole state suitable for maps at scales of about 1:5,000,000

**3**

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

**4**

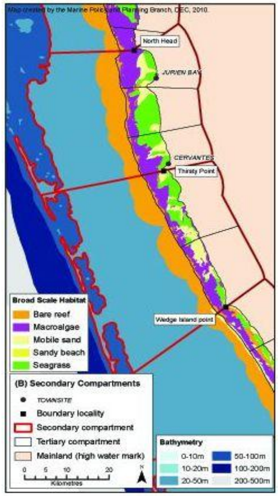


**Regions:** Areas with recurring patterns of landform and geology suitable for regional mapping at scales of approximately 1:250,000

**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**

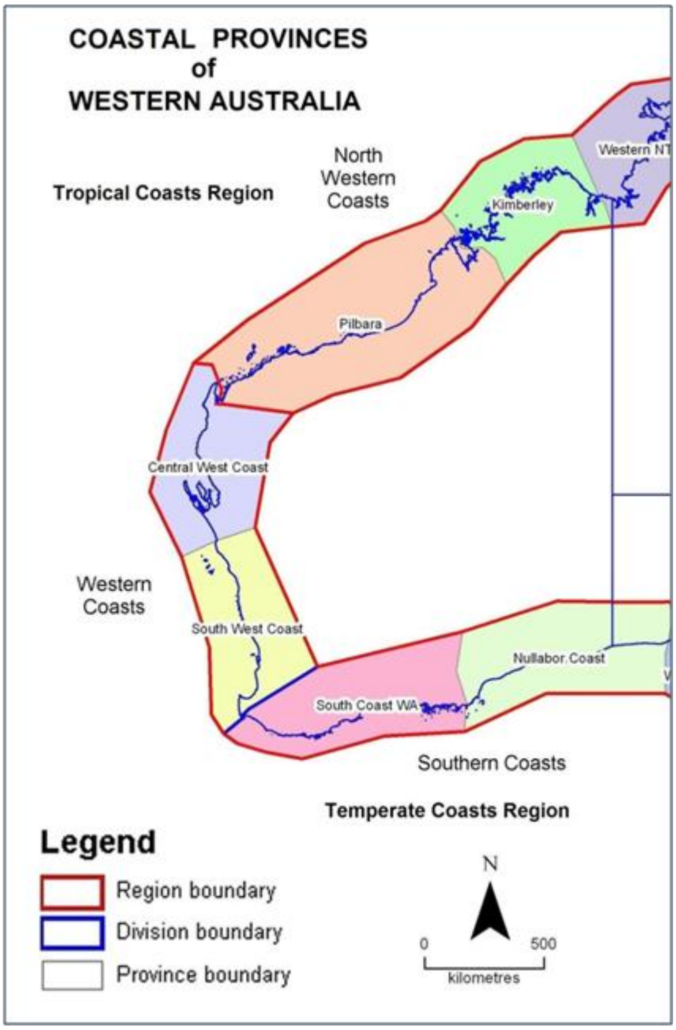



**Figure 3-2: Coastal provinces in Western Australia**

## 3.1. GEOLOGY

The study area covers parts of three major tectonic units: west of Cape Preston is the Northern Carnarvon Basin; between Cape Preston and the De Grey River delta is the Pilbara Craton; while east of the De Grey River delta is the Canning Basin.

**Northern Carnarvon Basin**

The Northern Carnarvon Basin is dominated by a southwest-trending set of troughs – the Exmouth, Barrow, Dampier, and Beagle Sub-basins. These are the major Mesozoic depositional centres of the southern North West Shelf, containing up to 15 km of Mesozoic sedimentary rocks.

In the sub-basins, Mesozoic and Cenozoic successions overlie (commonly at considerable depth) Paleozoic sedimentary rocks that extend north form the Southern Carnarvon and Canning Basins. They are flanked shoreward by the Peedamullah Shelf and Lambert Shelf, and seaward by a mid-basin arch — the Rankin Platform and Alpha Arch. The Kangaroo Trough, Dixon Sub-basin, and Investigator Sub-basin lie farther offshore.

The evolution of the Northern Carnarvon Basin was controlled by the breakup of Gondwana. Prior to breakup, several sedimentary sequences were deposited from the Ordovician to the Permian in an elongate basin between the Archean Pilbara Craton and continental blocks to the northwest.

At the end of the Paleozoic, northeastward-trending troughs developed in the Northern Carnarvon Basin, and the present basin framework began to develop, as rapidly subsiding troughs in the Triassic, prior to faulting and breakup in the Jurassic.

Thick siliciclastic sequences accumulated in offshore marine to continental settings. Final continental separation did not occur until the Early Neocomian, further offshore than the attempted rifts along the axis of the Barrow and Dampier Sub-basins, leaving a trailing edge, passive margin basin.

Sometime after breakup, in the Late Cretaceous, global oceanic circulation patterns changed and deposition shifted from siliciclastic dominated to carbonate dominated, forming a thick carbonate wedge across the entire offshore basin.

**Pilbara Craton**

The Pilbara Craton is geologically one of the oldest regions in Australia, containing rocks that are more than 3600 million years old and represents one of the best preserved fragments of one of Earth's earliest continents.

The oldest part of the craton is a mixture of volcanic and sedimentary rocks, intruded by granite magma. These volcanic and sedimentary rocks continued to be deposited, and were intruded by more granite throughout the following 800 million years. During this time, huge stresses within this newly formed crust caused many rocks to be severely sheared, folded and faulted. The Earth's surface was a hostile place during this time, with little oxygen in the atmosphere, and only simple microbial life that formed stromatolites. Some of these are up to 3490 million years old – the world's oldest fossils and the first visible evidence of life on Earth. The world's oldest evidence of meteorite impacts also occurs in the Pilbara during this time (3460 to 2490 million years ago).

By about 2800 million years ago a major period of uplift and erosion took place. The Pilbara Craton at this time was part of a larger continent that began to break apart along what is today its southern margin where an extensive rift was formed into which a 'sea of basalt lava' was extruded, burying the older landscape. This was the beginning of the deposition of the vast Hamersley Basin.

As the main period of breakup came to an end by about 2690 million years ago, the Hamersley Basin began to fill with sediments deposited on a shelf or platform that opened to an ocean. During this time, extensive deposits of banded iron-formation (BIF) were laid down, such as those in the Hamersley Range.

Between about 2200 and 1800 million years ago, the ocean that lay to the south of the Pilbara Craton was closed during a series of collisions with other ancient continents to form the West Australian Craton. Extensive mountain building took place along this collision zone, leading to another major period of erosion and the formation of a sedimentary basin called the Ashburton Basin.

Around 1760 million years ago, the West Australian Craton collided with another continent to the northeast, called the North Australian Craton. This continental collision brought together most of what are now the western and central parts of the Australian continental landmass. Further collisions brought together a much bigger assemblage of cratons that formed the Rodinia supercontinent by 1000 million years ago.

Following the collisions, the crust then sagged over the junction between the cratons, allowing an immense basin to develop that filled with sediments deposited by shallow seas, rivers and glaciers. In the eastern part of the Pilbara, where the Little Sandy Desert is today, this part of the basin is called the Officer Basin. By about 750 million years ago Rodinia began to break apart and, although the Australian continent remained mostly intact, old 'joins' between cratons were reactivated.

Around 295 million years ago, Australia was part of the Gondwana supercontinent and lay close to the South Pole. Glaciers and ice sheets deeply scoured the landscape, carving huge glacial valleys that are recognisable today in the north-eastern part of the Pilbara.
Around 170 million years ago, a large rift developed within the crust off the northern side of the Pilbara, where the present day North West Shelf now is. This marked the beginning of the breakup of Australia from Gondwana.

During the last 90 million years, thick deposits of limestone have accumulated over the North West Shelf, some of which is now exposed as islands and coastal ranges.

**Canning Basin**

The Canning Basin initially developed in the Early Paleozoic as an intracratonic sag between the Pilbara Craton and Kimberley Basin. The basin contains two major northwesterly trending troughs separated by a mid-basin arch, and marginal shelves.

The northern trough is divided into the Fitzroy Trough and the Gregory Sub-basin, which are estimated to contain up to 15 km of predominantly Paleozoic rocks.

The southern trough includes the Kidson and Willara Sub-basins, in which there are thinner sedimentary successions (4–5 km thick) of predominantly Ordovician to Silurian and Permian age, with extensive Mesozoic cover. The central arch is divided into the Broome and Crossland Platforms, and structural terraces step down from it into the troughs on either side.

The subdivisions of the basin are based on presently expressed structural elements, although growth faulting initially developed some of these elements, and troughs developed and were active at different times during the basin’s history. The succession in the basin consists of continental to marine-shelf, mixed carbonate and clastic sedimentary rocks. Major evaporitic basins were present in the Ordovician, with lesser such accumulations in the Silurian and Early Devonian. Significant tectonic events affected the basin in the Early Ordovician (extension and rapid subsidence), Early Devonian (compression and erosion), Late Devonian (extension and subsidence), Middle and Late Carboniferous – Permian (compression then subsidence), and Early Jurassic (transpressional uplift and erosion). The southern Canning Basin is less intensely deformed than the northern part, the major fault block movements being absent in the south.

The offshore Canning Basin contains about 6000m of Permian and younger sedimentary rocks, with a thick Jurassic to Early Cretaceous section.

## 3.2. THE GEOLOGIC FRAMEWORK

At all scales, the geologic framework is a highly significant attribute of the Study Area. Together with the inheritance of riverine plains the rocky terrain of the region is a primary determinant of the susceptibility of the coast to changing metocean conditions. This is due to interaction of hard and soft rock terrain with marine processes and by provision of a foundation to the recently formed Holocene landforms. At a tertiary compartment level, or more detailed scale, tracts of coast may have landforms comprised of unconsolidated sandy sediments that overlie, or are perched, on a limestone or older rock surface well above present sea level. However the rock basement,is uneven in planform, hardness, elevation and depth below the unconsolidated sands. This diversity contributes to variation in the susceptibility of the coast. This variation can be addressed in by ensuring there is 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 pertinent to the Pilbara coast because a large proportion of the unconsolidated Holocene landforms in the Study Area overlie, or are perched on, irregular rocky and sedimentary structures inherited from older geologic times (Semeniuk 1996). In many instances the Holocene deposits occur as cheniers and spits tied to rock outcrops. Additionally, small dune barriers have formed in places. Many of these have retreated barriers that have migrated landwards since 6000 years ago and exposed rock inshore or along the active beach. The underlying rocky terrain is commonly comprised of older coral platforms and beachrock ramps. Some of the cheniers have lithified cores of coastal limestone. The rocky terrain provides the framework in which the coast is developing through its interaction with unconsolidated sandy sediment and coastal processes. The interaction is fundamental to the manner in which the coast has evolved and will continue to develop. It also determines the susceptibility of the coast to future environmental change.

At a local scale the presence or absence of rock outcrops in the shoreface 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, Cleary *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 2013). Secondly, Silvester (1974), Hsu & Evans (1989) and Sanderson (2000) have discussed the roles of shoreface topography in determining the plan shape of beaches. 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.

## 3.3. LAND SYSTEMS

Land systems have been mapped and described for the Study Area to 10km landward of the Landgate Mean High Water Mark, extending further inland to incorporate the Holocene and Alluvial Land Systems in the three Areas of Planning Interest (Figure 3-3; Appendices C-D).

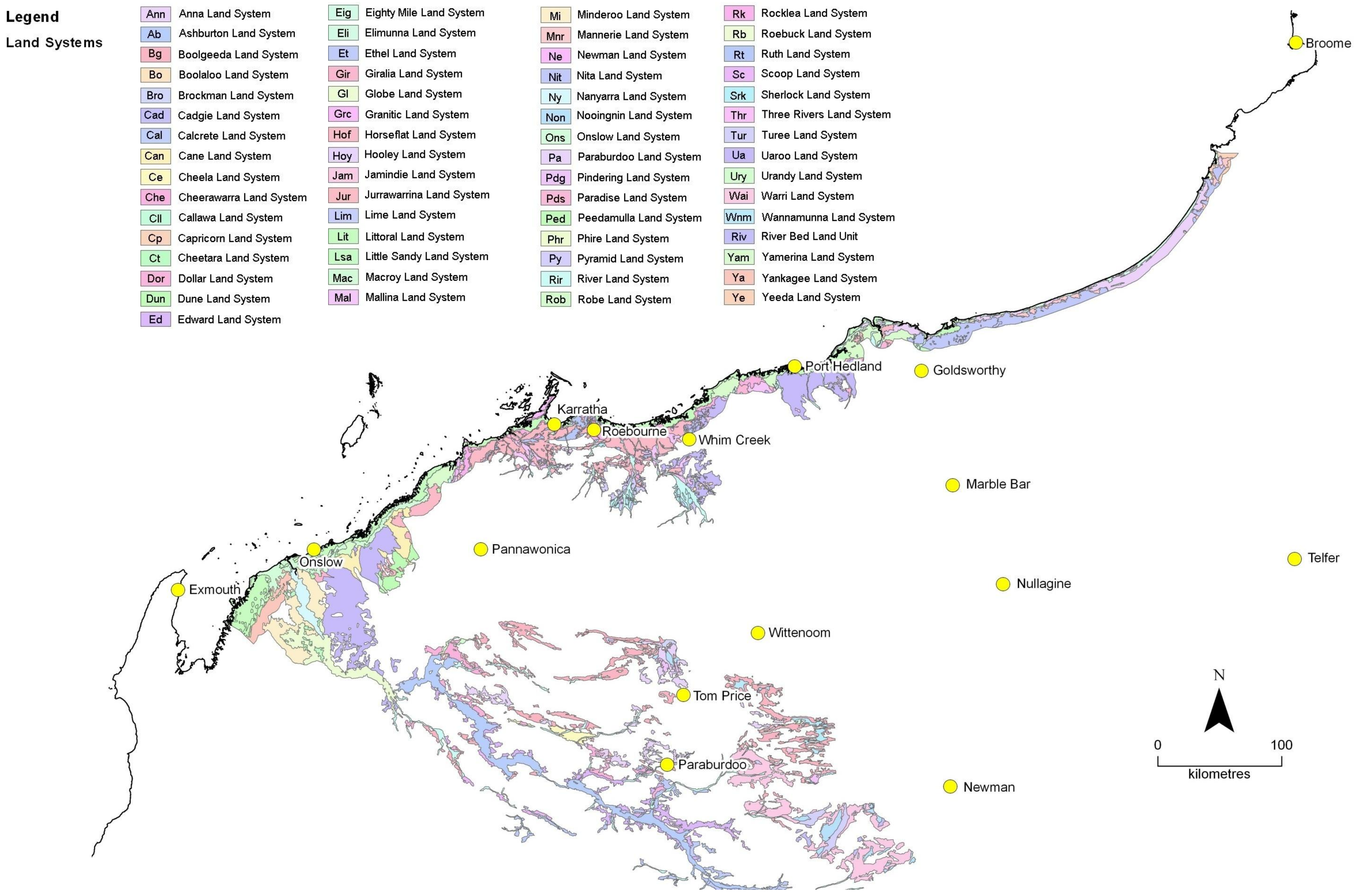



**Figure 3-3: Coastal and Holocene Alluvial Land Systems for the Tertiary Compartments**

## 3.4. MAJOR LANDFORM ASSOCIATIONS

Major land form associations and landforms were classified according to stability and instability criteria compiled separately for four coastal zones in the Study Area the inner shelf, subtidal shoreface, intertidal shore and onshore areas (Section 2.3). The land system structure and landform stability describing each ranking level have been taken from conceptual models described in the geological and geomorphologic literature as well as derived from field observation and interpretation of aerial photography. The associations are commonly complex due to marked interaction between an inherited terrain; a veneer of modern Holocene sediments; and the complex interplay between riverine and riverine and marine processes. It is difficult to isolate one component for description or analysis without invoking the others.

Ranking of individual land systems and landforms within each landform association indicates the likelihood of geomorphic change and may be used as a proxy for the effects of local scale variations in coastal processes. At all scales the formation and structure of landforms is tied to the geometry of the inner continental shelf, particularly its width; embayment dimensions and aspect; shoreline orientation; the geology, inherited deltaic features, including river channels, overbank basins and tidal creeks; and the available supply of sediment. Variability of these factors along the Pilbara coast has been examined for each tertiary compartment and the vulnerability of each compartment or cell classified according to the criteria listed in Table 2-7.

On the inherited morphology of river deltas and riverine plains, major riverine and marine processes affecting some landform associations encompass all four coastal in the Study Area. These processes include river flooding, tidal creek incursion and storm surge inundation of the lowlands. The major processes and landforms associated with them are separately described below. Criteria used to estimate the structure and stability of landform associations and landforms with rivers and tidal creeks in the Pilbara region are described below, followed by description of criteria applied to landform associations and landforms from the specific coastal zones.

### 3.4.1. Rivers

Rivers and streams have a direct role in coastal evolution through flooding; their ecological functions; and in sediment supply and storage. Coastal vulnerability is determined by fluvial processes through development of floodplains on inherited and active outwash plains and river deltas; infilling of inherited basins and topographic lows formed as overbank basins on prior floodplains or as coastal lagoons developed under mid-Holocene or earlier conditions of high sea level; and supply of sediments to the inshore wave and current systems that transport it along the coast. Additionally, channelized fluvial discharge redistributes sediment eroded from the coastal lowlands and initially deposited as subaqueous levees and bars at the river mouths. In contrast to dominantly riverine processes overland flow is commonly drained seaward by tidal creeks with channels extending across subtidal terraces flanking the shore.

Rivers are associated with mobile landforms and modify the supply of sediment to the coast. These are manifested as the migration and switching (avulsion) of river channels, the formation of meanders and billabongs, changes in river terrace and bar patterns, development of levee banks, and almost constant change to configuration of the river mouth and its bar formations. An example is provided by historical changes to the mouth of the Ashburton River that lead to abandonment of the original townsite of Onslow and the siltation of its harbour (Damara WA 2010a). The morphology of inherited outwash plains and deltaic environments indicates the rivers and creeks of the Pilbara coast have been highly changeable. It includes complex assemblages of palaeochannels, gorges and overbank or backwater basins indicative of channel avulsion on river dominated deltas. The present-day rivers are also highly changeable. They alter from being a sediment source during flood events, to potentially acting as sediment sinks for intervening periods when river flow is quiescent.

The major rivers of the Pilbara coast, the Ashburton, Fortescue and De Grey Rivers; as well as the smaller Cane, Robe, Maitland, Harding, Sherlock, Yule and Turner Rivers intermittently deliver large volumes of sediment and water to the coast. For example sediments from the Ashburton River have contributed to the formation of barrier dunes between the Turbridgi and Coolgra Point, with sediment also accumulating on the inner continental shelf in the vicinity of the Sandy Islands archipelago. During significant flood runoff, sediment also may be released from deltaic features in the path of the river flow, including beaches, bars and inshore areas. Additionally, sediment can also be supplied to the coastal system from the banks and bed of the alluvial channel, from flooded alluvial or estuarine flats and from the catchment. After a scour event, the scoured channel and inshore area will act as a sink, trapping sediment until the bar has reformed, then becoming a feature that can be bypassed by alongshore sediment transport. While the bar is acting as a trap, it can potentially starve the downdrift coast until the bar is reformed and full sediment bypassing resumes. Potentially river mouths could act as sediment sinks for decades following a significant flood event.

The physical contribution of rivers to coastal evolution varies between individual systems. It depends on catchment size and structure; sediment availability in the catchment and stream channel; stream distributary network and palaeochannels; whether the outflow is constrained in inherited channels or diffused as overland flow across pre-existing floodplains; connectivity with tidal creeks; geologic control at the point of discharge; and the nature of the inshore substrate over which it flows. These factors are listed in the criteria used to determine the susceptibility of *Onshore Structures* (Table 2-7; Figure 2-12) and instability of the shore as it is affected by *Rivers and Tidal Creeks* (Table 2-7; Figure 2-14; Figure 2-15).

### 3.4.2. Tidal Creeks

Perillo (2009: 185) pointed out that tidal creeks are the basic circulatory system through which water, sediments, organic matter, nutrients as well as pollutants are transported in and out of coastal wetlands, which include mudflats like those of the arid Pilbara. Paraphrasing and adding to Perillo’s (2009: 185) comments: the tide pumps water through networks of tidal creeks crossing mudflats thus facilitating exchange with the open ocean and the exportation of materials (including pollutants) from it. The impacts of tidal creeks on unconsolidated lowlands vary with the interaction of sea level fluctuation, storm surge and tidal regime over periods ranging from short-lived individual weather events to interdecadal and longer variation in sea level. As a rising tide inundates coastal wetland, such as mudflats, or mangroves, it first becomes channelized until water level overflows channel banks and levees and develops a sheet flow across the mudflat. This process is exacerbated by coincidental rise in sea level, such as that due to storm surge or the nodal cycle (Eliot 2010). Silty sediment pushed by a rising tide may be deposited in a distributary fan on the mudflat surface, thereby presenting a loss of material from the coast but contributing to basin fill (Figure 3-4A) and floodplain development (Eliot *et al.* 2005; Winn *et al.* 2006). Ebbing is the reverse process, first water recedes as sheet flow across the higher ground of mudflats but final drainage is through the tidal creeks and across subtidal terraces fringing the shore. The drainage may lead to headwater gullying (Figure 3-4B) and encroachment of the creek network across the mudflat. This results in loss of sediment from the mudflat and lowering of its surface (Mulrennan & Woodroffe 1998; Cobb *et al.* 2007).

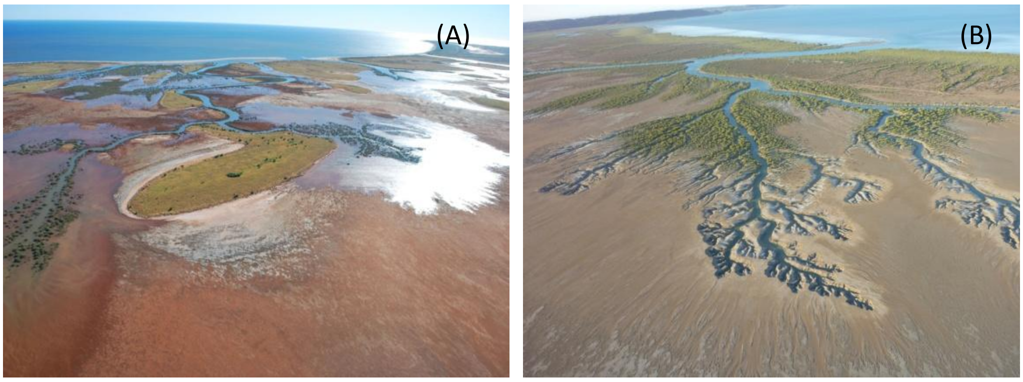



**Figure 3-4: Tidal Creek Headwaters**
**(A) Left: Overbank levees and headwater fans deposited at the headwaters of a tidal creek under flood tide conditions; (B) Right: Headwater gullying of tidal creek network due to surface runoff across mudflat at Karratha. The photograph was taken at low tide.**

The form of tidal creeks in the region ranges from runoff drains to large networks of tidal channels that are permanently open. The drains support tidal flows temporarily operating as open channels while river flood and groundwater conditions keep them open and last until marine processes, particularly littoral drift close their entrances. River flooding and inundation by storm subsequently may cause relocation of the channels, particularly where they become blocked by spits, cheniers or storm bars. In this context tidal creeks are highly dynamic and the connectivity between the marine and terrestrial environment provides an indication of the relative stability of different coastal compartments and sediment cells. Hence attributes of tidal creek have been used as criteria ranking the stability of the subtidal shoreface, intertidal shore and onshore areas; respectively describing the shore, upper intertidal and supratidal components of the compartment or cell being examined. The attributes include the distribution (number per length of shoreline) and extent of network development (Table 2-7; Figure 2-15).

Sediment availability in areas of mudflats, the areas inundated by flood tide along the tidal creeks is also affected by the width of the mudflat present and features of the shoreline

(*Tidal Flats-shoreline features* category for Instability; Figure 2-17) and surge zone (*Mudflats-landward features* category for Instability; Figure 2-19) that affect sediment redistribution. Such features include vegetation cover, presence and continuity of cheniers, and presence and development of tidal creeks.

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

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

### 3.4.3. Inner Shelf Morphology

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

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

A wide and shallow shelf increases the potential surge and decreases the potential incident wave energy. The inner shelf structure can reduce some of the incident wave energy, largely as a result of friction and refraction, with some influence of wave breaking and diffraction across northern Exmouth Gulf, in the lee of islands and adjacent to the Burrup Peninsula (Figure 4-7). Islands may further modify inshore processes through altering the wave direction due to refraction and diffraction, creating a wave shadow in their lee. This may result in sediment deposition in the wave shadow area, cause current amplification between the island and land and lead to locally enhanced alongshore sediment transport.

The shelf structure is indicated in Figure 1-1, in the Department of Transport and Australian Navy navigation charts, Geoscience Australia bathymetry, datasets for the North West Shelf region held by the Australian Geological Survey Organisation (Heyward *et al.* 2006: 24) and survey records presented by Harris et al. (2005). The influence of inner shelf structure on inshore metocean processes is included in the assessment of vulnerability through the *Inner Shelf Morphology* category for Susceptibility (Table 2-7). The susceptibility to surge and waves is ranked based on shelf width, with consideration of sheltering by archipelago and remnant barrier chains. There is an inverse relationship in shelf widths that may produce the most exposed wave climate (narrow shelf) and most exposed surge climate (wide shelf). The measured shelf width from the Landgate MHWM to the 20m isobath was used directly for the wave climate and converted to an effective shelf width for surge climate to incorporate the major forcing processes.

The susceptibility ranks for both factors were combined using a matrix approach (Table 3-1) with modifications for further shelter of wave energy by islands. The highest susceptibility rank is applied to a compartment with (1) high wave climate & moderate or high surge climate or (2) high surge climate & moderate or high wave climate. The lowest susceptibility is for a compartment with both low wave and surge climates or sheltered by an archipelago or remnant barrier chain. The three rankings in between incorporate the varied exposure to surge and wave climates according to Table 3-1.

The shelf width for wave climate was directly proportional to the shelf width, based on the friction factor being approximately proportional to the cube of the shelf width (USACE 1984). Incident wave energy is further modified in the subtidal and intertidal zone by reefs, banks, rock pavements, coastal aspect and orientation, presence of islands and promontories.

An effective shelf width was derived for the surge climate based on the product of measured shelf width, the relative likelihood of extreme cyclonic activity and a direction factor.

**Table 3-1: Ranking for Inner Shelf Susceptibility**
**Shelf Width for Wave Climate and Effective Shelf Width for Surge Climate**

| | | Surge Climate | | |
|---|---|---|---|---|
| | | Effective Narrow (<12km) | Effective Moderate (12-25km) | Effective Wide (>25km) |
| Wave Climate | Wide (>40km) | (1) | (2) | (4) |
| | Moderate (25-40km) | (2) | (3) | (5) |
| | Narrow (<25 km) | (4) | (5) | (5) |

### 3.4.4. Subtidal Shoreface

The influence of changing metocean conditions on coastal sheltering provides an over-riding control on coastal landform change. Hence, the influence of rocky terrain on inshore metocean processes is included in the assessment of vulnerability through the *Subtidal*

*Shoreface Structure & Coastal Orientation* category for Susceptibility and *Inshore Substrate* category for Instability (Table 2-7). The proximity of rock to the coast and its surface structure (width, depth, roughness and gaps) modify the local metocean processes in the lee of reefs and islands (Silvester & Hsu 1993; Mc Ninch 2004). The water level, waves and currents interact with rock outcrops to modify the inshore processes, including sediment transport and water circulation patterns (Sanderson & Eliot 1996; Damara WA 2010a, 2010b; GEMS 2010a, b). *Subtidal Shoreface Structure & Coastal Orientation* classes the highest susceptibility rate for a planar shoreface without reef and the lowest susceptibility for bare rock as reefs or pavements (Figure 2-7). The other rankings incorporate concepts of varying subtidal rock continuity and structure. *Inshore Substrate* classes the most unstable inshore areas as those without any rock outcropping and the most stable as those with almost continuous rock cover or hard rock that has a high resistance to erosion (Figure 2-13).

Coastal orientation, or the direction to seaward the coast faces, further alters the potential storm surge and marine inundation to which it is susceptible. In the present analysis coastal orientation is included in the assessment of vulnerability through the *Subtidal Shoreface Structure & Coastal Orientation* (particularly orientation) category for Susceptibility (Table 2-7). It is considered in relation to the exposure to major storms with NE winds impacting shallow and deep NE facing embayments. These are environments in which storm surge is likely to be amplified, given no offshore constraints, and is an area where evidence of unusually high water levels have been found.

### 3.4.5. Intertidal Shore

Rocky headlands, cliffs and perched beaches are significant features of the Pilbara coast. The inherited rocky terrain extensively underlies and in places outcrops through unconsolidated sediments, some of which are also inherited. The rocky terrain influences coastal vulnerability because it affects responses of the accretionary landforms that overlie and abut it to change in metocean processes. Several forms of rocky headlands, cliffs and perched beaches are recognised in the criteria used to assess vulnerability (Figure 2-9). Broadly following Sunamara (1992), these include plunging cliffs, cliffs and rock platforms, gently sloping rocky coast and beachrock shores. All are found in the Study Area. The high cliffs occur around Burrup Peninsula and along the Cleaverville coast. Low bluffs are common to parts of the coast where coastal limestone has formed; for example between Forty Mile Beach (Gnoorea) and Pelican Point, and along the ocean side of Finnicane Island. Rocky headlands and high cliffs provide vantage points along the coast, control points for shoreline configuration, and topographic control of stream and tidal creek discharge; as occurs at the mouth of the Fortescue River and Cleaverville Creek. Beachrock ramps with tempestites boulder deposits are common along several sections of rocky coast, such as the coast between Port Hedland and Cooke Point.

The diversity of rock formations in the Study Area is matched by the structural integrity of the materials of which they are comprised, which ranges from the comparatively soft Pleistocene limestones forming the core of coastal ridges in the vicinity of Port Hedland to the hard Achaean igneous rocks of the Burrup Peninsula. The coastal limestones have different degrees of stability depending on their composition, the extent to which they have been consolidated since deposition of the sediments comprising them, and the degree of degradation the exposed formations have undergone since exposure to metocean processes. A risk assessment of the coastal limestones in the vicinity of heavily accessed areas would be appropriate in those parts of the Pilbara region if they have not been undertaken already.

Rocky headlands have long been recognised as providing topographic control for the plan shape of the shoreline (Bascom 1980: 14; Silvester & Hsu 1993: 302-312; Masselink & Hughes 2003: 237-241). As part of the rock framework comprising the coast they directly affect the adjacent shore and commonly determine the degree to which the shore is locally exposed. This is particularly significant where the coast is comprised of extensive peninsulas such as Cape Preston, Cape Lambert and the Burrup Peninsula. The embayments adjoining them are subject to different degrees of exposure. Commonly they have been cut in inherited riverine plains and now support a sandy shore overlying and fringed to seaward by reef platform or pavement. Shorelines, especially those in the western part of the region are linked by limestone platforms, protected by lithified cheniers and dune ridges, or are partially sediment filled where rivers discharge into them. Many headlands in the region have platforms supporting perched beaches, such as those described by Green (2008), da Silva (2010) and Gallop *et al.* (2011).

Perched beaches are included in the assessment of vulnerability largely though the *Intertidal Shore* category for susceptibility (Table 2-7; Figure 2-9; Figure 2-10). The stability of a perched beach is determined by the elevation of the underlying rock structure in relation to water levels, although this has not been included in the criteria describing coastal stability. The perched beaches least vulnerable to environmental change are those where the rock elevation is above high tide and the least stable are perched on a shallow pavement. However, perched beaches can occur on a smaller spatial scale than the sediment cell and should be considered in any local assessment.

East of Cape Lambert headland promontories are smaller although they may still restrict the extent of sediment movement along the coast and form NE facing embayments that are exposed to strong winds and waves. They may also have localised effects on beaches adjoining them. For example, spits, bars and cheniers associated with sediment bypassing are tied to small headlands at Anketell and Cape Thouin. These unconsolidated landforms adjoin dune ridges abutting or overlying rock. High level wrack (debris) lines have been observed at these sites. Shell samples taken from the wrack lines and submitted for radiometric dating to extend the record of extreme sea level events in the region (Section 4.2.2). Additionally, the type of dune barriers developed at bay heads or in the embayments between successive headlands is a function of sediment supply which may be restricted by headlands or redirection of longshore transport.

The stability of barriers and dunes is included through the *Frontal Dune Complex* category for Instability (Table 2-7; Figure 2-16). Barriers may migrate landwards under the extreme onshore wind and high sea level conditions occasionally occurring in the Pilbara. The retreat occurs as a response to localised blowout of foredune and frontal dune ridges, wind scouring of the seaward face of the ridges without apparent deposition to landward, and breaching of the ridges by sea level inundation. Hence the capacity of the frontal dune complex to withstand present metocean forcing is principally a function of the barrier width and height, with large episodic transgressive barrier being the least susceptible to environmental changes associated with the onset of high sea levels. Low receded barriers are most susceptible to storm impacts and commonly subject to washover and realignment, unless perched on high rocky terrain. 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 and whether a third level ranking under *the Hinterland Topography* category is warranted (Figure 2-18).

### 3.4.6. Onshore Landforms

Away from the immediate shore, the most common onshore landforms are the riverine plains, outwash plains and deltaic landform associations and landform, together with the mudflats discussed above. The upper intertidal and supratidal components of the mudflats support a variety of landforms indicative of the extent of extreme inundation by storm surge or tsunamis, both of which occur in the region. The landforms include features listed in Table 2-7 under the *Hinterland Topography* category and illustrated in Figure 2-18; namely alluvial flats, coastal dunes, longitudinal dunes on floodplains, palaeochannels, residual mounds and tidal creeks in places. The coastal dune fields include a variety of barrier structures considered in the criteria.

Coastal sand barriers are apparent in areas where there is an accumulation of unconsolidated sediment close to a river supply, as in the vicinity of Urala and east of the Fortescue River. Processes underlying barrier formation and the diversity of landforms associated with them have been widely discussed; for example see reviews by Roy *et al.* (1994), Hesp & Short (1999a) and Masetti *et al.* (2008). In a seaward sequence the main barrier features match those of a retrograding coastal sand barrier comprising active and inactive parabolic dunes and/or foredune ridges as well as the beach and shoreface as described by Cowell & Thom (1994) and Hesp & Short (1999a).

The susceptibility of barriers to change is a function of barrier type and size. Following the nomenclature of Roy *et al.* (1994), the largest and least susceptible to change are episodic transgressive barriers which have undergone phases of dune activity leading to development of a dune ridge through the formation of foredunes, blowouts and nested parabolic sand dunes as the ridge migrates landwards. The most susceptible to change due to metocean forcing are mainland barriers where a thin wedge of sand abuts rocky coast. However, there are differences between the Australian East and West Coasts. The principal distinction is that dunes forming the WA barriers commonly overlie rocky terrain and therefore are comparatively less susceptible to change due to metocean forcing. Hence Roy *et al.* (1994)’s model has been combined with the degree to which the barrier system is affected by the geological framework to determine its susceptibility to change through the *Onshore Structures Including Barriers and Deltas* category for Susceptibility (Table 2-7; Figure 2-11). In the Study Area the barriers least susceptible to extensive erosion are either large episodic transgressive barriers or barriers perched on high rock surfaces. Several show evidence of having been wind scoured during extremely high wind events. The most susceptible to change are mainland beaches fronting cliffs or bluffs or unconsolidated spits and cheniers.

# 4. Coastal Processes

This section documents the regional metocean forcing. 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 Pilbara coast.

The metocean forcing is reviewed using wind, tropical cyclone track, water level, wave, rainfall and discharge datasets. The variability and influence of these processes are described at a regional scale in Section 4.2, with further local scale considerations required (Section 4.3), within the context of observed and future coastal change. The geomorphic processes relevant to the Areas of Planning Interest are described for Onslow (Section 6.2.1), Karratha (Section 6.3.1) and Port Hedland (Section 6.4.1).

## 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 2012a) 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 2012a; 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.

Within the Pilbara coast, the structure and formation of landform units (subtidal terraces, beaches, dunes, mudflats, deltas, cheniers and spits, and coastal barriers) are strongly tied to the river systems and their sediment supply, geology (the topography of the inner continental shelf, islands, nearshore reef systems and rock outcrops at the shoreline) and inherited deltaic features.

The structure and relative dominance of rivers, the inner shelf, islands, nearshore reefs and outcrops of rock at the shoreline delineates the coastal landforms according to the five primary compartments of the Study Area (Table 2-1; Figure 1-2; bathymetry shown in Figure 1-1). Each primary compartment experiences varied metocean forcing at a regional scale due to the inner shelf influence, islands, aspect and sheltering; and at a local scale through further modification to processes by the river and creek systems, and the varied nearshore and inshore geologic structure.

**Table 4-1: Primary and Secondary Coastal Variables (NCCOE 2012a)**

| 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, islands, rivers, 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.

**Table 4-2: Sensitivity of Landform Units to Environmental Parameters for a Sandy Coast**

| 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 |

For this study, the relative importance of different processes has been considered with respect to nine landform unit components described in Section 2.4. In general terms, there is a progression in time scales from rapid response at the beach scale, through to gradual, slow change for barrier systems (Masetti *et al.* 2008), sub-tidal terraces and tidal flat complexes (Perillo & Piccolo 2011), and deltaic systems (Perillo 2005).

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

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

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

## 4.2. REGIONAL SCALE

The Pilbara coast is located approximately between latitudes 18°44'S and 22°10'S and longitudes 114°27'E and 121°37'S on the north-northwest-facing coast of Australia, including eastern Exmouth Gulf and the Dampier Archipelago.

The Pilbara coast is a region of extremes. It is noted for its areas of high tide and the occurrence of extreme weather systems, particularly the seasonal impact of tropical cyclones and storm surges in an otherwise arid environment. These deliver floods and marine inundation events that leave their mark on the landscape and drive geomorphologic change on a coast which has a highly diverse range of landforms. Tidal, surge and runoff interactions are significant and occur across the Pilbara's extensive coastal lowlands, up to 20km inland. The river channels, riverine outwash plains, river deltas, tidal flats, coastal dunes, cheniers and spits, wide subtidal terraces and extensive sand shoals of the coast are all subject to significant change under extreme meteorologic and oceanographic conditions. These active landforms abut and overly a very complex and old terrain cut into the hard-rock Archaean geology of the Pilbara Craton and the more recently formed sedimentary rocks it supports.

At a broad regional scale there is a paucity of historical information describing metocean processes. Exceptions are research conducted in certain areas or related to certain projects. Informaton has been collected for:

- Exmouth Gulf (eg. Steedman & Russell 1986; Brown 1988; Nott & Hubert 2005; Heyward *et al.* 2006);

- North West Shelf oil and gas projects including onshore facilities and pipelines such as at Macedon, Ashburton North and Dampier Archipelago (Steedman Limited 1987; Buchan & Stroud 1993; Hamilton 1997; Pearce *et al.* 2003; Heyward *et al.* 2006; Damara WA 2006b; GEMS 2007, 2008, 2009; Chevron Australia 2010; DHI 2010);
- Ports, jetties and salt works at Onslow, Dampier, Anketell Point, Cape Preston, Point Samson and Port Hedland (Gulf Holdings 1990; GEMS 2000a, b, 2003, 2004, 2006, 2008b, c, 2009, 2010a, b; Metocean Engineers 2004; Damara WA 2006c, 2010a; GEMS & JFA Consultants 2010; Oceanica & Damara 2011; API 2010, 2011; BHP Billiton 2011);
- Present and proposed marine parks and conservation reserves, including the Dampier Archipelago Islands Nature Reserves, proposed Dampier Archipelago/Regnard (formerly Cape Preston) Marine Conservation Reserve, the proposed Burrup Peninsula Conservation Reserve, the proposed Monetebello/Barrow Islands Marine Conservation Reserve and the proposed Eighty Mile Beach Marine Park (CALM 1990; Osborne *et al.* 2000a, b; CALM 2005; DEC 2005, 2007, 2011);
- Flood risk and water supply, focusing on river and creek systems and groundwater behaviour with some interaction with storm surge (River stage measurements from Department of Water; HGM 1990; JDA 1995; Ruprecht & Ivanescu 2000; Aquaterra 2004; Department of Water 2009; Magee 2009; GHD 2010a; JDA 2010a, b; URS 2010b; Cardno 2011; GHD 2011; JDA *et al.* 2011a, b);
- Design of roads and bridges (e.g. CMPS&F 1999; Egis 1999;Damara WA 2010b); and
- Aeronautic purposes, with meteorologic information collected at townsites and airfields to assist with plane and helicopter operations (Bureau of Meteorology weather station network from 1886 onwards; BoM 1972, 1996, 1998; Pitt & Mills 1985).

This information has been used to describe the regional metocean forcing of the Pilbara.

### 4.2.1. Meteorology

The climate of the Pilbara coast reflects its location at around 20°S latitude in the sub-tropical high pressure belt, with its southern limit at the boundary between the Temperate and Tropical Coast Regions (desert and grassland Köppen zones in Stern *et al.* 2000). The region experiences an arid sub-tropical (sub-monsoonal) climate, which is hot throughout the year, with typically low but variable rainfall falling during both summer and winter seasons. The majority of weather systems experienced are extra-tropical in origin, although occasional tropical cyclones are associated with almost all the severe wind observations on record. During summer months, rainfall mainly occurs from thunderstorms, with a highly variable contribution from tropical cyclones (Milton 1980). A Bureau of Meteorology regional climate summary is not available for the Pilbara, with summaries for the two adjacent regions Gascoyne-Murchison (BoM 1998) and the Kimberley (BoM 1996).

**Weather systems**

Synoptically, the region is dominated by relatively diffuse extra-tropical high pressure systems, although during the Austral summer months, the influence of tropical low pressure systems increases. The meteorology of the Northwest Shelf is controlled by two main seasons, referred to here, respectively as ‘cool’ and ‘warm’; there are short transition seasons between these two main seasons. The cool season typically extends from May to August, with the warm season normally from October through March (Pearce *et al.* 2003).

Overlying the prevailing seasonal winds is a local circulation brought about by land/sea breeze cells. These cause a regular diurnal variation in the strength and direction of winds, for approximately five to twenty kilometres both landward and seaward from the coast. Although these cells are strongest during the warm season, they may occur at any time of year. Prevailing wind conditions may also be disturbed for several weeks during the passage and aftermath of tropical cyclones, or for longer periods associated with destabilisation of the heat trough, albeit with much milder influence.

The warm season is largely coincident with the tropical cyclone season, which may produce intense, mobile low-pressure systems. These are capable of causing locally extreme winds and are generally associated with the most extreme rainfall, wave and surge conditions across the North West Shelf (Dare & Davidson 2004). However, their typically small scale and radial wind structure determines that their impact is highly dependent on their path and relative proximity (Nott 2006).

During the **'cool season'** a high-pressure ridge controls the winds over the region; this ridge is a persistent feature over the southern part of Western Australia. The ridge drives easterly winds across the Northwest Shelf. Frontal systems moving through mid-latitudes periodically erode the ridge; winds then shift to the northeast, with subsequent rotation through southwest to southeast following frontal passage. A new high pressure will then re-establish the pattern; during this phase periods of more persistent and stronger easterly winds can be expected to influence the area.

During periods of calm weather, local weak sea breezes may develop along the coast, directionally dependent on the particular location. Figure 4-1 shows a typical synoptic sequence over the WA region during June. The sequence initially shows a strong high-pressure system directing a north-east pressure gradient over the Pilbara, then a weakening of this gradient as the high erodes under the influence of a mid-latitude front and finally the re-establishment of high pressure in the wake of the front.

During the **'warm season'** months, the sub-tropical ridge migrates southwards and the dominant synoptic feature is a permanent heat trough that develops inland from the Pilbara coast, associated with continental heating. This pattern produces quasi-permanent southwest wind flow across the Shelf region. Fluctuations in the intensity and location of the heat trough as well as diurnal and local topographic influences affect day-to-day variations in wind direction and speed within the general southwest flow. Figure 4-2 shows a typical synoptic pattern over the WA region during January. During this period, the winds on the coast are controlled by the location and intensity of the Pilbara heat low.

The relative intensity of seasonal winds is known to vary on an inter-annual basis. This behavior loosely corresponds to global climate variations, as described by El Nino-Southern Oscillation modes, with stronger easterly conditions typical during the La Nina phase and stronger westerly conditions during the El Nino phase. This pattern is in addition to local variations in the Indian Ocean climate.

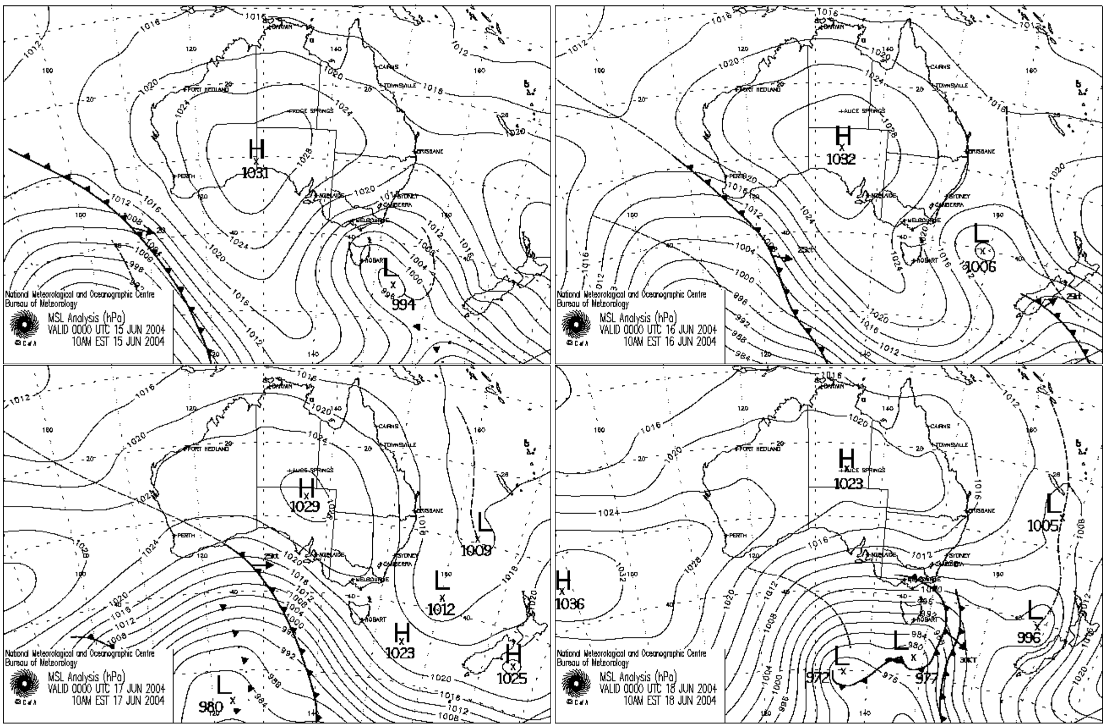



**Figure 4-1: Example of Common 'Cool Season' Synoptic Evolution**

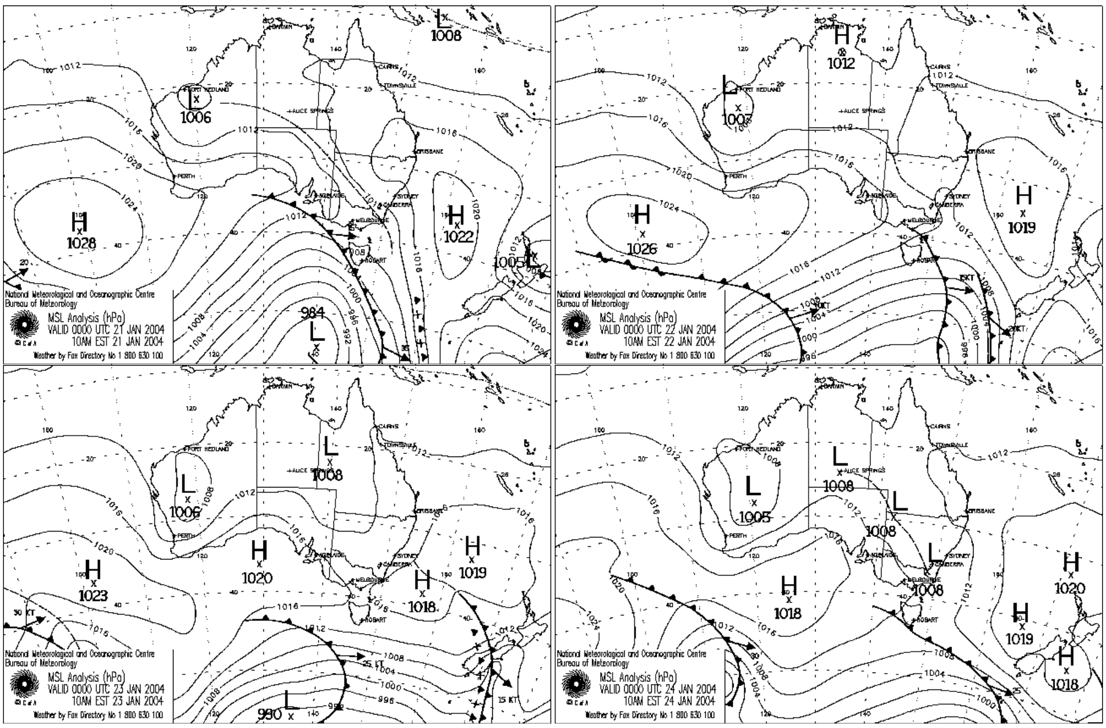



**Figure 4-2: Example of Common 'Warm Season' Synoptic Evolution**

**Storm events**

Weather systems and their interactions may generate conditions of strong winds, waves, surge and rainfall. These dominant conditions modify sediment supply and transport patterns, result in storm erosion, potentially modify unstable landforms and can generate terrestrial and coastal flooding. Storm conditions are associated with the following weather systems, with significant spatial, seasonal and interannual variability (Steedman & Russell 1986; Steedman Limited 1987; BoM 1996, 1998; GEMS 2000a & b; Damara WA 2008; Eliot 2010):

Winds
- Tropical cyclones, with occasional tornadoes and water spouts
- Thunderstorms, with occasional tornadoes and water spouts
- Seabreezes
- Weather systems interacting with fronts to the south

Surge
- Onshore wind events due to tropical cyclones, which are most extreme when systems cross nearby and to the west of open coast sites
- Tropical cyclones travelling parallel to the coast generating shelf waves

Rainfall
- Tropical depressions including tropical cyclones, tropical lows and associated thunderstorms are the dominant warm season rain systems
- The Australian monsoon has occasional fringing influence in the eastern Pilbara from December to March
- Northwest cloudbands, particularly connected to mid-latitude depressions to the south are the dominant cool season rain systems
- Thunderstorms

Northwest cloudbands are a cloud mass forming off the northwest coast and extending southeast towards the continent. Their formation is due to lifting of moist tropical air by cold air intruding north, associated with a strong mid-latitude trough or cold front to the south. Northwest cloudbands are the primary cloud system that produces rainfall in the cooler months of the year from April to September, most frequently in May and June (Wright 1997; BoM 1996, 1998; Telcik 2003).

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

Tropical cyclones are discussed separately below as they are the dominant weather system of the Pilbara.

**Tropical Cyclones**

Tropical cyclones within the Pilbara have long been recognised as the synoptic conditions driving the most severe winds, waves, water levels, currents and flooding associated with either heavy rainfall or ocean storm surges (Hearn & Holloway 1990; Middelman 2007; Hemer *et al*. 2008). 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).

Consequently, these storm systems are studied in great detail, with the Bureau of Meteorology maintaining a tropical cyclone database that holds information on events since 1906 (Coleman 1972; Lourensz 1981; Dare & Davidson 2004). 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, use of the database to estimate the frequency of coastal hazards requires considerable interpretation, as (i) instrumentation methods have changed significantly causing spatial and temporal biases (Lourensz 1981; Harper *et al.* 2008); and (ii) the physical scale of tropical cyclones is small, such that measurements of "direct hit" cyclone effects by metocean instrumentation is relatively infrequent. The latter factor may strongly limit the ability for instrumented data to adequately provide cyclone model calibration or validation (Resio *et al.* 2009).

The most common approach towards estimating tropical cyclone risk is through the use of numerical modelling, parameterised by key variables such as cyclone central pressure, radius to maximum winds, direction and speed of travel. A large sample of tropical cyclones are required to describe hazards probabilistically, with observations often supplemented by the use of synthesised tropical cyclones. This approach has progressively advanced since early regional assessments (Hopley & Harvey 1976; Hubbert 1991; Harper *et al.* 2009; Hardy *et al.* 2010), although comparison of results using similar methods clearly demonstrates that there can be considerable variation of estimated flood levels due to small differences in the modelling approach (CMPS&F 1999; Damara WA 2008; Damara WA 2010b). Significantly, the small spatial scale of tropical cyclones and the loose relationships between winds, surges, waves and rainfall determines that studies relevant to one location or one form of impact may have low relevance to description at other sites or other impacts. These differences strongly disrupt the use of scenarios for which a single event is considered an "N-year event" for multiple impact parameters, and consequently have further supportedthe probabilistic approach to cyclone modelling.

*Tropical Cyclone Incidence*

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). The Pilbara coast is more cyclone prone than any other part of Australia with a high incidence of tropical cyclones offshore (Figure 4-3) coinciding with a region of intense tropical cyclones between Port Hedland and Exmouth. Figure 4-3 shows the total count of tropical cyclones within 1° latitude-longitude cells, for 1909 to 1999, from the Bureau of Meteorology tropical cyclone database. This underestimates event frequency due to a lack of instrumentation before 1959. Nevertheless, high incidence of tropical cyclones offshore from the Pilbara coast is clearly illustrated. Typically three to five cyclones might approach the Pilbara coast during the cyclone season (Berthot & Treloar 2009), with one to two causing destructive winds (Damara WA 2011a).

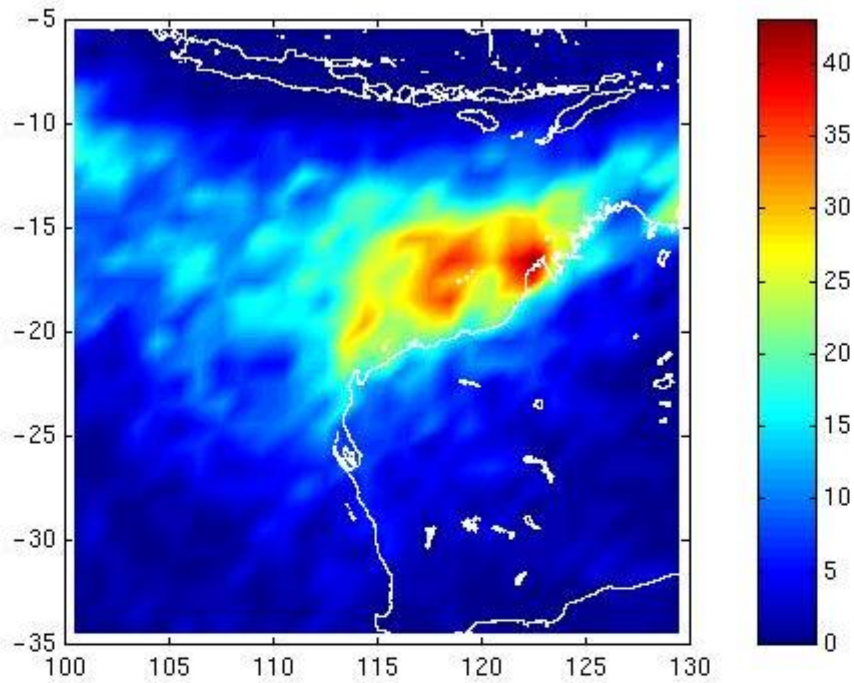



**Figure 4-3: Total Count of Tropical Cyclones from 1o Lat-Long Grid**

The regional variation of cyclone central pressure is indicated by Figure 4-4, which shows the extremely low central pressures that may occur in the Pilbara region. It is important to note that the derived central pressure recurrence intervals are highly dependent upon the scale of the evaluation, with smaller areas generally having less intense systems for a given ARI (Heideman & Mitchell 2009). For large areas, the relationship can be approximated by a scalar length, such that a $5^{o}x5^{o}$ lat-long cell gives central pressure ARI that are approximately $^{1}/_{5}$ those that are generated by a $1^{o}x1^{o}$ lat-long cell. It is due to this scale effect that the impact of a 100 year intensity cyclone derived from a regional analysis does not correspond to a 100 year coastal flooding event.

*Tropical Cyclone Surge, Waves and River Flows*

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

Cyclonic **surge** is comprised of three principal components, being pressure surge, wind setup and wave setup (Pugh 1987; Bode & Hardy 1997). Surges can be particularly large in the Pilbara due to the intense nature of cyclones in the region and the presence of a broad continental shelf which enhances wind set-up. The highest surge for each site is generally associated with intense tropical cyclones which cross the coast to the west producing extreme onshore winds and waves (Damara WA 2008; Figure 4-5). More frequent moderate surges are associated with tropical cyclones travelling parallel to the coast, providing strong shelf-parallel winds. It is understood that this causes shelf wave formation, which allows a sustained surge signal to propagate along the coast (Gill & Schumann 1974; Fandry & Steedman 1994).

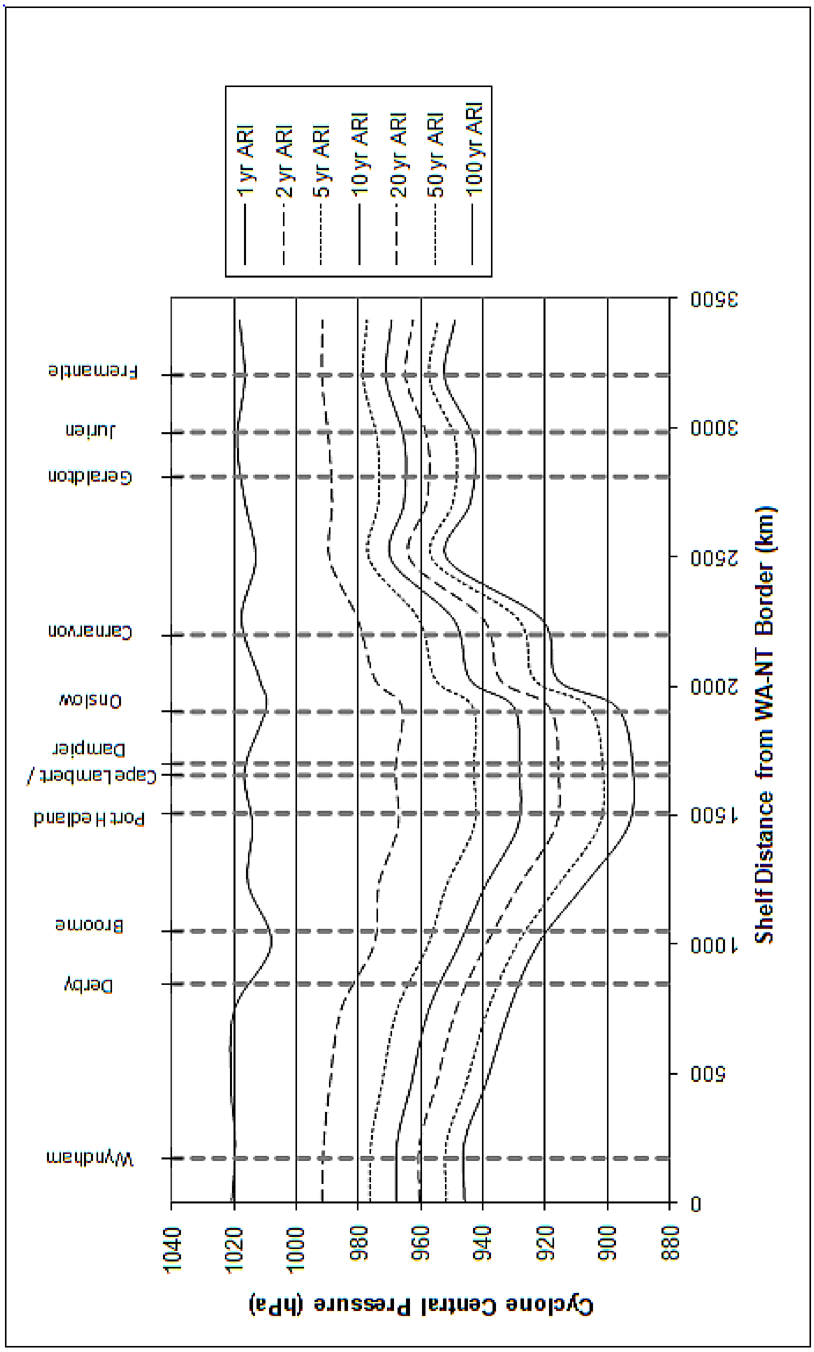



**Figure 4-4: Regional Variation in Cyclone Minimum Central Pressure Derived from 5° Latitude-Longitude Cells (Source: Damara WA 2009)**

Due to their radial structure, tropical cyclones may produce strong **winds** in any direction and the time-sequence of wind direction observed at a location is dependent on its path and proximity. The greatest winds are experienced near the centre of the system and therefore the highest recorded winds at a particular site are typically from systems tracking within close proximity. Tropical cyclone winds may generate energetic **wave** conditions. The waves may be a complex function of the system path and the resultant time-varying fetch, developed by the relative motion of wave and cyclone centre (Damara WA 2009). Under situations where the cyclone system is travelling at a similar speed to wave propagation, 'trapped-fetch' conditions may occur, producing highly amplified wave conditions (Buchan *et al*. 1999; Alves *et al.* 2004; Bowyer & McAfee 2005).

High **river flows** are largely associated with tropical cyclones that recurve towards the southeast across the Pilbara causing heavy rainfall on the river/creek catchments. For example TC John in 1999 created high flows in the Yule, Sherwood and Turner Rivers (Figure 4-5C) and TC Monty In 2004 caused flooding of the Ashburton, Robe, Fortescue and Maitland Rivers and overflow of the Harding River dam (BoM 2011). Major flooding of the river systems in the Pilbara can also occur from tropical lows, with rainfall totals commonly greater than 100mm. The most significant flooding occurs once a catchment is already saturated, with sequential events generating widespread flooding.

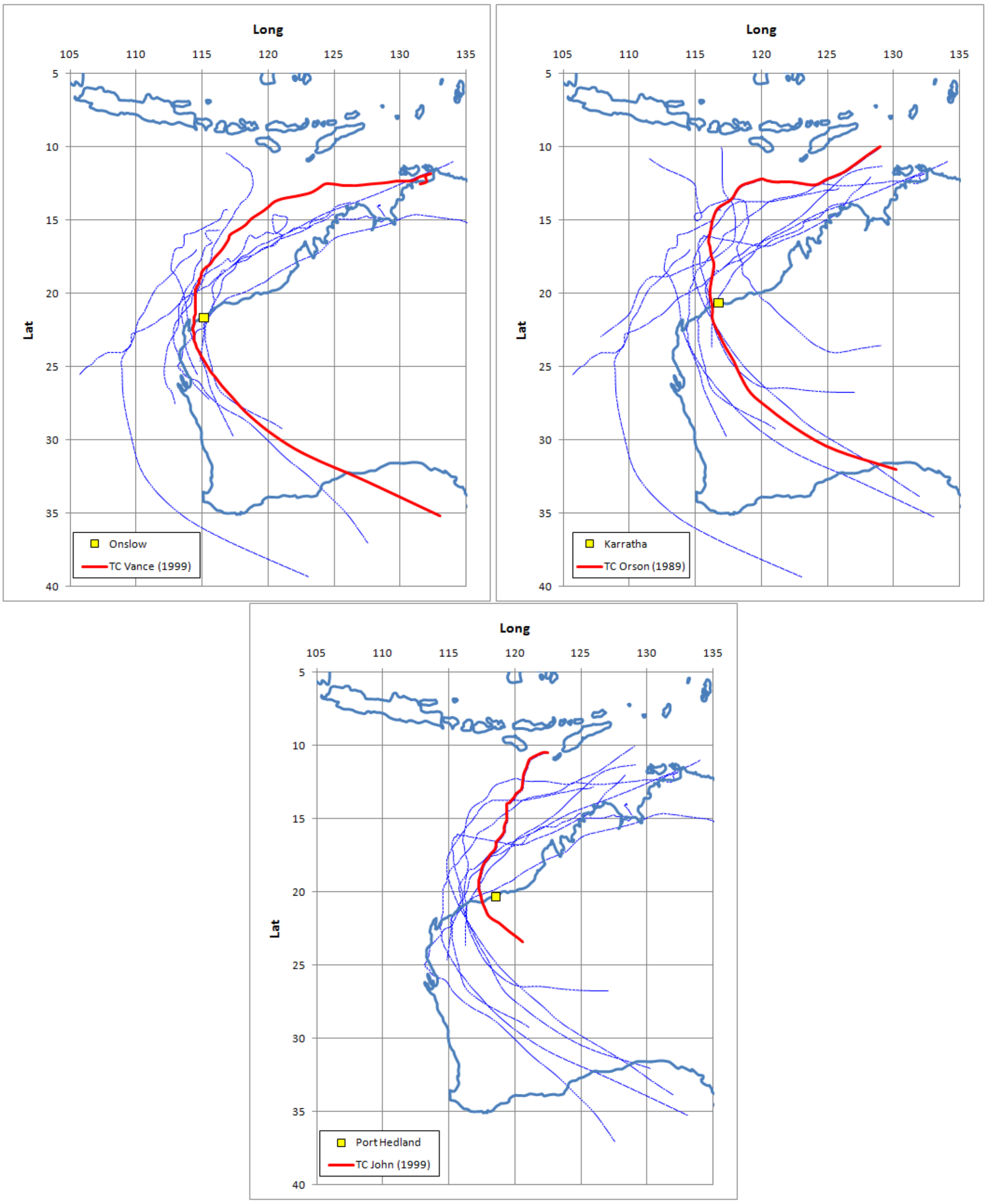



**Figure 4-5: Tropical Cyclone Paths Causing Greatest Surge**
**(A) Onslow (1985-2008) and (B) Karratha (1982-2008) (C) Port Hedland (1988-2008)**
**(Source: Damara WA 2008)**

### 4.2.2. Water levels

Water level processes experience a significant variation across the Pilbara region, with major changes caused by the regional variation in tidal range, variation of continental shelf structure, change in coastal aspect and influences of embayment structure. Key water level processes affecting the Pilbara include tides, cyclonic surges, seasonal ranging and inter-annual mean sea level variations (National Tidal Facility 2000).

The Pilbara region experiences mainly semi-diurnal tides with tidal ranges typically increasing to the north (National Tidal Facility 2000) with LAT to HAT of 3.0m at Onslow, 7.5m at Port Hedland and 10.5 m at Broome, north of the Study Area (Department of Defence 2010). Local variations are determined by the influence of factors which modulate tide, such as shelf and embayment structure, where the water body is resonant with a particular cycle, or where frictional effects cause tidal currents to slow or focus (Damara WA 2008). The tidal forcing contains a range of cycles, including the semi-diurnal ranging, the monthly spring-neap cycle, bi-annual cycles of semi-diurnal tides due to movement of the solar equator and a 4.4 year cycle developed from lunar elliptic motion (Damara WA 2008; Eliot 2010).

The bathymetric structure, aspect and gulf shoreline structure configuration also modify the influence of non-tidal water level processes, including storm surges and resonant phenomena. Surge is mainly attributed to tropical systems and can be particularly large due to the presence of a broad continental shelf which enhances wind set-up and the intense nature of cyclones in the region. Surge may be enhanced by bathymetric features including transitions from deep water to wide and shallow shelf; or funnelling into convergent gulfs or embayments (Gönnert *et al*. 2001). Offshore reef chains or an irregular coastline may reduce the effects of wind setup (Damara WA 2006a).

To some extent the large tidal ranges in the region, particularly in the north of the Pilbara, mitigate the influence of tropical cyclone surges, as it is less likely that large storm surges will coincide with spring tide high water conditions (Cardno 2011). For example at Port Hedland , approximately 97% of water level observations are more than 1.0m below HAT, and 84% are more than 2.0m below HAT (Figure 1), which determines that a very large surge is required to generate extreme water levels, unless it is coincident with high spring tide (Damara WA 2010b).

Water level processes are described for the Pilbara coast by a summary of the previous analysed sustained water level measuring stations at Onslow, King Bay (Dampier), Cape Lambert and Port Hedland (National Tidal Facility 2000; Damara WA 2008; Eliot 2010). All stations were installed in the 1980's with King Bay (1982 to present) providing the longest most complete record.

The water level climate has a distinctly tidal character with perturbations from mean sea level variations and surge events. Mean sea level variations are largely attributed to changes in the strength of the Leeuwin Current and movement of regional atmospheric pressure belts.

The timing of seasonal variations in water levels is such that they are generally coincident for a portion of the cyclone season (Table 4-3; Damara WA 2008; Eliot 2010). This generally restricts the potential for high water levels to a relatively narrow time frame from March to April (Damara WA 2008):

- The semi-diurnal constituents vary bi-annually, with equinoctial peaks in March and September;
- Surge peaks due to tropical cyclones mainly occur December -March;
- The seasonal mean sea level peaks during March-April.

**Table 4-3: Peaks in Water Level Components (Source: Damara WA 2008)**

| Location | Tide Peaks | Surge Peaks | MSL Peaks | Peak |
|---|---|---|---|---|
| Broome | Mar, Sep | Feb-Apr | Mar | Feb-Apr |
| Port Hedland | Mar, Sep | Dec-Apr | Mar-Apr | Mar-Apr |
| Cape Lambert | Mar, Sep | Dec-Mar | Mar-Apr | Mar-Apr |
| King Bay | Mar, Sep | Dec-Mar | Apr | Mar-Apr |
| Onslow | Mar, Sep | Dec-Mar | Apr | Mar-Apr |

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

**Unusually Extreme Water Levels**

Issues related to determination of an advised setback to potential development and the advised elevation of footings for establishment of built structures inevitably arise in coastal planning and management. A means of estimating these values is to examine the lateral extent and elevation due to water inundation of coastal land during extreme events. In the Pilbara such events are reportedly associated with the occurrence of tropical cyclones (Power & Pearce 2007; Damara WA 2008, 2009) and tsunamis (Nott& Bryant 2003; Pattiaratchi & Wijeratne 2009; Geoscience Australia & Fire and Emergency Services Association 2010), although the extent and elevation of inundation associated with them are not always recorded systematically.

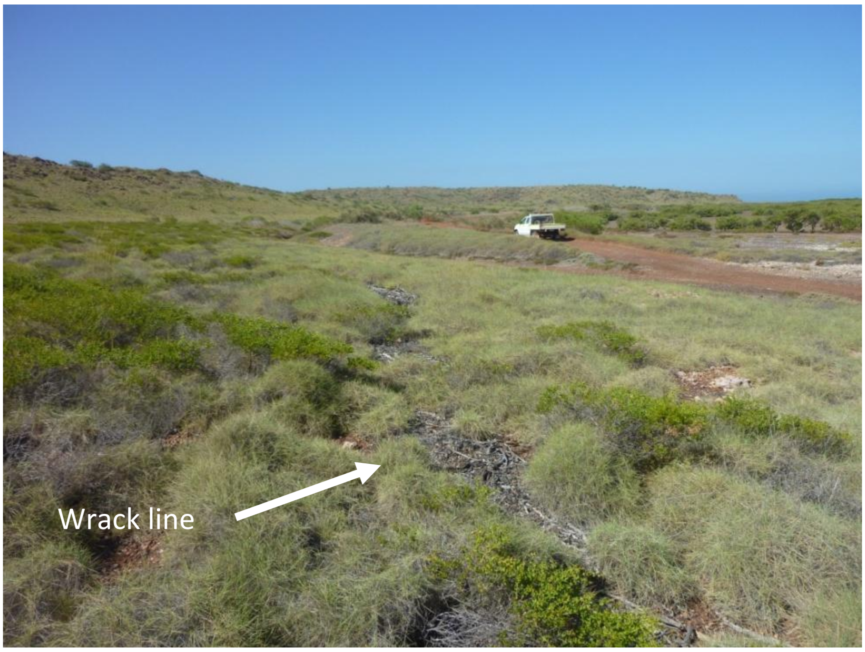
In recent decades large amounts of infrastructure have been built to support the Pilbara mining and North West Shelf Gas industries. Substantial towns and ports have also been established. More major infrastructure developments are in the planning stage or being built in the region, including expansion of the towns of Onslow, Karratha and Port Hedland (WAPC 2012). Risk of unusually high surges and tsunami events does not appear to have been built into considerations relating to human safety or potential damage to engineering works in the region. In the light of recent events elsewhere it would be timely for serious consideration to be given to the risks. The observations reported here are of an exploratory nature to indicate the potential scope of the problem. Further, more detailed and accurate surveys are required to substantiate observations made in the field.

As part of a survey of geomorphological features of the region it became evident that there are a number of wrack lines at a series of relatively uniform elevations on dune, chenier and spit faces along the coast. Two types of wrack lines were discernible. First, wrack lines at different elevations varying from close to spring high tide up to approximately 5m above present high tide level were apparent near the mouths of tidal creeks, on foredunes or close to the landward margins of mudflats. These were comprised of plant remains, leaves and wood, as well as shell and other debris such as plastic bottles (Figure 4-6A). The volume of woody drift material of terrestrial origin indicates an origin that may be linked to storm surge associated with recent cyclones such as Tropical Cyclone Vance (March 1999) and Dominic (January 2009). Second, a group of wrack lines, lacking plant remains but dominated by marine shell, and coral in places, occurred at levels of up to approximately 10m above GPS estimated mean sea level (Figure 4-6B). The second group of raised wrack lines were of particular interest and were observed high on frontal dunes and on the crest of inactive chenier spits and bars. These elevation features commonly stretch for many hundreds of metres and each wrack line is generally confined to a height range of 1-2 m.

The raised wrack lines were examined and shell samples obtained from several locations, including Casugrina Point, Sunset Beach, Horseshoe Island and Urala Station around Onslow as part of as geomorphic surveys for Chevron (Dodson& Eliot 2011), and at Cleaverville, Anketell, Cossack and Balla Bella as part of the current project. The latter were examined and sampled to obtain an understanding of the regional distribution of the features. Additionally, a range of sites were visited at Gnoorea, Nickol Bay and Burrup Peninsula, Depuch Island, Port Hedland and Eighty Mile Beach near Cape Keraudren. No raised wracklines were observed at these sites.

Sites with raised wracklines were photographed, GPS co-ordinates including height above mean sea level recorded and shell material was collected for radiocarbon dating. *Anadara* (mainly *A. crebicostata*) and Oyster (sp.) shell samples obtained from high level wrack lines as part of the Chevron Australian project (Dodson & Eliot 2011) were measured for radiocarbon in the laboratories of the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney. Additionally, two living shells of *Anadara* sp. were also treated and measured to estimate the size of the marine reservoir effect in the region. Radiocarbon ages are reported as calendar ages calculated using the IntCalib (2010) computer program (Dodson & Eliot 2011). The results are listed in Table 4-4. They indicate the unusually high water levels occurred well after sea level rose to its present position approximately 6000 years before present are recent events.

During field surveys for the current, coastal planning project 16 samples were collected and have been submitted to ANSTO for radiometric dating. They include two from dunes the vicinity of the Fortescue River; two from chenier spits in SW Nickol Bay; one on a storm bar at Karratha; three from spits and bars at Cleaverville; four from similar locations at Anketell; and two from cheniers close to the historical Balla Bella townsite. The high level wracklines investigated in this study were dominantly *Anadara crebricostata*. They are generally found independently of tidal creek locations and are seen along the shores of mudflats and frontal dunes of the open coast. Significant features of the field observations were the similarity in the range and types of landforms on which the wrack lines were found as well as their panregional distribution. The radiometric analyses are in progress. Hence results are not available for the purposes of his report but will be reported separately.




**(A) Low-level wrack line SE Cleaverville**

Debris comprising the wrack line includes plant remains, leaves and wood, as well as shell and anthropogenic debris such as plastic bottles.


**(B) High-level wrack line exposed in sand quarry SW Nickol Bay**

Debris comprising the wrack line was mainly *Anadara crebricostata* that occurred in a band below the surface of a spit in the lee of a rocky outcrop.

**Figure 4-6: Wrack Lines Left by Water Inundation of Landforms in the Pilbara Region**

Our working hypothesis is that the wrack lines were from exposed ocean reefs as the sea first withdrew then were picked up as a tsunami surge crossed the reef and carried them forward into the coastal dunes, and in some cases up streams and into bordering mudflat basins. They have different composition and distribution to materials associated with cyclones, in that wood was absent. The latter could be a function of age of the deposits. From the record the higher levels suggest these were of much greater magnitude than observed storm surges in terms of their effects. However, it is also likely they may have been deposited by surges associated with unusually extreme tropical cyclones with intensities similar to or larger than TC Larry in Queensland (Bureau of Meteorology 2007, 2011) and Hurricane Katrina in the USA (NOAA 2005). Regardless of whether the high water levels were driven by tropical cyclones or tsunamis, such events are irregular but appear to have a recurrence interval in the order of 500 years. It would be appropriate to consider their likelihood in any coastal planning decisions.

**Table 4-4: Wrack Line Radiometric Dating and Elevations near Onslow (Source: Dodson & Eliot 2011)**
**Note: Samples from Urala Station, Casugrina Point and Sunset Beach are for elevations well above HAT. The sample from Second Creek was high on the bank of the stream and close to its mouth.**

| Site | Elevation above MSL (metres) | Material | Date Code | $\delta^{13}$(‰) | Conventional Radiocarbon age years BP (1δ error) | Calendar Age AD (2 δ error) |
|---|---|---|---|---|---|---|
| Second Creek | 1-2 | Living *Anadara crebicostata* | OZN119 | 0.1±0.1 | Modern | Modern |
| Urala | 6-8 | Oyster | OZN110 | 2.2±0.1 | 545±45 | 1303-1441 |
| Casugrina Point | 8-10 | Oyster | OZN110 | 1.9±0.1 | 695±30 | 1264-1387 |
| Sunset Beach | 6-8 | Oyster | OZN111 | 2.4±0.1 | 1590±30 | 411-542 |
| Horseshoe Island | 2-4 | Oyster | OZN114 | 1.9±0.1 | 490±30 | 1405-1449 |
| Second Creek | 4-6 | Oyster | OZN112 | 2.1±0.1 | 700±30 | 1262-1387 |

**Tsunami**

Tectonic activity along the southern margin of the Indonesian archipelago has provided an active source of earthquakes and volcanic eruptions capable of generating tsunami that affect Western Australia, including the Pilbara coast. There is a modern record of moderate tsunami activity for Western Australia, with palaeotsunami evidence suggesting larger events have occurred. The majority of evidence is interpretive in nature (Bryant & Nott 2001; Nott & Bryant 2003).

Along the Pilbara coast, wrack identified at Onslow and Karratha (Dodson & Eliot 2011; Bryant & Nott 2003; Simpson *et al.*2007) and boulder deposits identified at Dampier (Bryant & Nott 2003) possibly have been caused by tsunami's. In particular, Dodson& Eliot (2011) concluded that at least three high magnitude or more likely tsunami events (between 6 and 14m above present mean sea level) have impacted the coast in the vicinity of Onslow in the past 2000 years and it is noted that wrack lines of similar elevation have been found at Cleaverville, Anketell, Cossack and Balla Balla as part of the current project.

Modern observations of tsunami in the Pilbara region have included:

- March 2005, July 2006 and September 2007– all tide gauges along the WA coast recorded tsunamis during these events with the July 2006 event most prominent at Dampier where a tsunami of 0.8m was recorded (Pattiaratchi & Wijeratne 2009);
- 2004 Boxing Day – observed along the entire WA coast with a 1.14m tsunami recorded at Carnarvon south of the Study area (Pattiaratchi & Wijeratne 2009). Anecdotal evidence at Onslow included that all the water drained out of the bay several times and then came in again very fast each time (Simpson *et al.* 2007);
- June 1994 – examination of the damage revealed the tsunami would have reached heights of 2–3 m between Exmouth and Dampier (Pattiaratchi and Woo 2000). Anecdotol evidence at Onslow suggested that the tide was 1 m higher than it should have been during an event that may correspond to the 1994 tsunami (Simpson *et al.* 2007);
- 1977 tsunami –at Point Samson, six to eight 4–6m high waves were observed, and in Dampier, four waves of 2–2.5m in height were observed (Pattiaratchi & Wijeratne 2009);
- September 1937 – known to have affected Onslow to the east of the Study Area where anecdotal evidence noted Beadon Bay was reportedly awash with seaweed, coral and other debris such that swimming was prohibited for at least three days following the tsunami. (Simpson *et al.* 2007);
- 1883 Krakatoa–a maximum run-up height of 1.5 m was observed at Cossack (Pattiaratchi & Wijeratne 2009). Anecdotal evidence in the form of a letter dated the 18th September 1883 documents a tsunami event in Onslow "swamping" a dingy and leaving another "washed up high and dry" (Simpson *et al.* 2007);

Despite their relative rarity, the potential extreme scale of tsunami has prompted detailed hazard assessment and modelling (Legget 2006; Simpson *et al.* 2007; Burbidge *et al.* 2009; Geoscience Australia & Fire and Emergency Services Association 2010). Detailed modelling has been conducted for the Onslow region, including collation of anecdotal evidence (Simpson *et al.* 2007) and for six communities along the North West Shelf (Geoscience Australia & Fire and Emergency Services Association: GA & FESA 2010).

Modelling of tsunami propagation from the southern arc of the Indonesian Archipelago has indicated that the earthquake location, magnitude and orientation have a strong effect on coastal tsunami impact in the Pilbara (Legget 2006). Furthermore, tsunami propagation is strongly influenced by offshore bathymetry. For example focusing of tsunami energy towards the coast occurs at the Exmouth Plateau in the western part of the study area (Legget 2006; GA & FESA 2010; Figure 4-7).

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

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

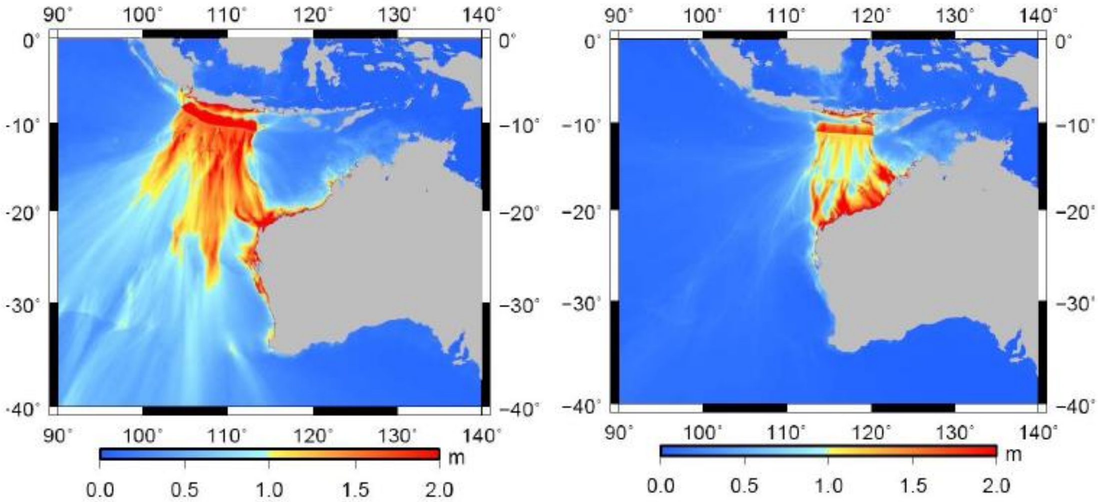



**Figure 4-7: Modelled Tsunami Scenarios**
**(A) Magnitude 9.3 Earthquake off Java and (B) Magnitude 9.1 Earthquake off Sumba**
**(Source: GA & FESA 2010)**

### 4.2.3. Waves

With the exception of the occasional extreme waves associated with tropical cyclones, the Pilbara shelf experiences a generally mild wave climate and sea states tend to be heaviest from the northeast in winter (June and July) and lightest in late summer (April) when they come typically from the west and northwest (Hayes *et al*. 2005). The waves along for the North West Shelf have been identified (Pearce *et al*. 2003; Metocean Engineers 2004) as coming from four sources:

- Southern and Indian Ocean swells, propagating past Northwest Cape;
- Winter easterly swell generated across the Timor Sea;
- Locally generated wind waves; and
- Wind waves generated by tropical cyclones.

Spatial variation of the swell wave climate is suggested by a wave hindcast from 1997 to 2002 (Figure 4-8; Li *et al.* 2008). The hindcast suggests the Indian Ocean swells dominate along the Pilbara with increased influence to the west, such that southwest swells provide the prevailing wave offshore conditions. However, due to sheltering from the continental landmass, these swell waves are significantly damped closer to shore with the large change of modal direction clearly indicating the role of refraction. Consequently the nearshore wave climate is strongly influenced by locally generated wind waves and occasional tropical cyclones.

The model results also show significant spatial and temporal variation in wave height occurring across the inner shelf in depths less than 50-100m, corresponding to the varied structure of the inner shelf of the primary compartments and the dominant wave source. The presence of Islands, the varied aspect, shelf, gulf/bay and reef structure of the coast, in the context of the transition in forcing mechanisms, restricts the ability to represent the Pilbara area using individual datasets. In addition, it should be noted that numerical wave models tend to misrepresent locally generated wind waves, along with waves induced by tropical cyclones, partly attributed to limitations with the wind inputs (Jensen *et al.* 2006).

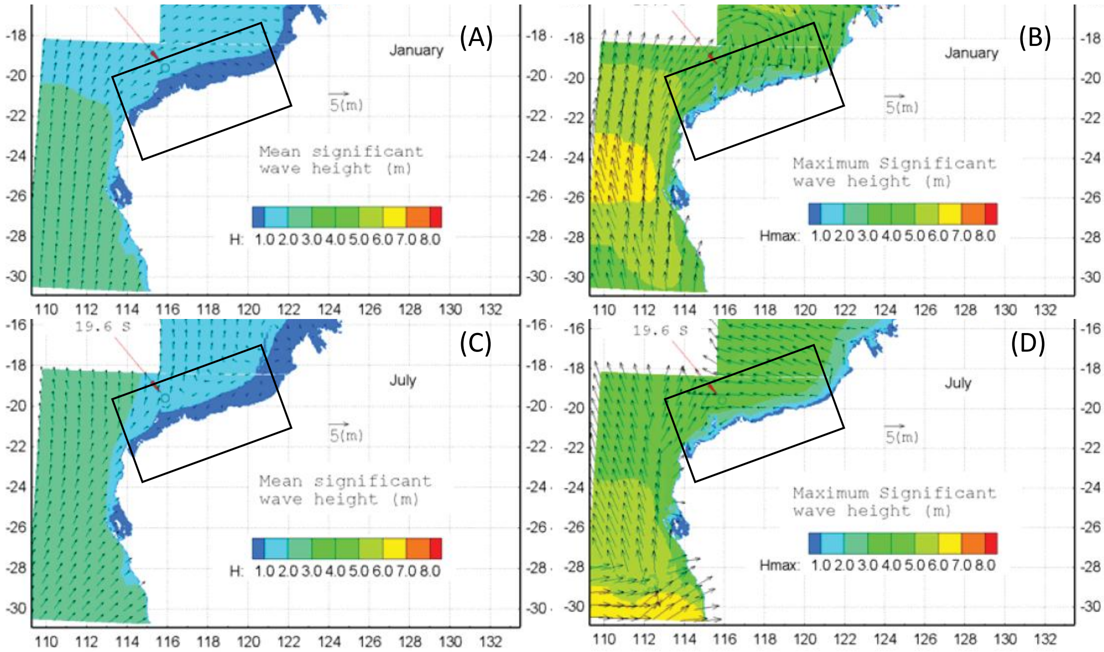



**Figure 4-8: Indicative Variation of Significant Wave Heights Based on 1997-2002 CSIRO WAM Wave Hindcast (A) January mean, (B) January maximum, (C) July mean and (D) July maximum (After: Li *et al*. 2008) Note: Study Area Shown in Black Box**

### 4.2.4. Currents/Circulation

The continental shelf offshore from the Pilbara region increase in width to the east, with varied influence of islands, archipelagos and peninsulas. With the exception of regional off-shelf currents, the influence of islands and peninsulas limit the geographic extent to which circulation measurements may be related. Consequently, the majority of available information regarding circulation in the Pilbara region is relevant to regional offshore currents, measured at specific nearshore sites or generated using numerical models (Section 4.2). The main sources of information have been collected in Exmouth Gulf, for Northwest Shelf gas projects and their onshore facilities, port facilities and marine parks. The information is summarised in review papers (Buchan and Stroud 1993; Osborne *et al.* 2000a, b; Pearce *et al.* 2003; Hayes *et al.* 2005; Heyward *et al.* 2006; Pattiaratchi 2008); and more site-specific recent investigations such as for Wheatstone (Chevron Australia 2010), Anketell Point (API 2011) and the Port Hedland Outer Harbour (BHP Billiton 2011).

On the continental shelf, circulation may be driven by multiple processes, each of which may have greater or lesser influence under different bathymetric or synoptic conditions (Csanady 1997). In theory, four principal circulation drivers are oceanographic (steric gradients and weather systems), tidal, wind-driven (local winds) and wave driven processes. These have a general sequence of dominance moving seawards that relates to the relative influence of the forcing mechanisms (Figure 4-9; Damara WA 2010a).

In general, the boundary effect of the coast causes most surface currents in the nearshore to run nearly shore parallel. This pattern can be modified by the influence of reefs, islands and channels and density driven currents in shallow areas. Further offshore the surface current direction becomes more responsive to the direction of forcing.

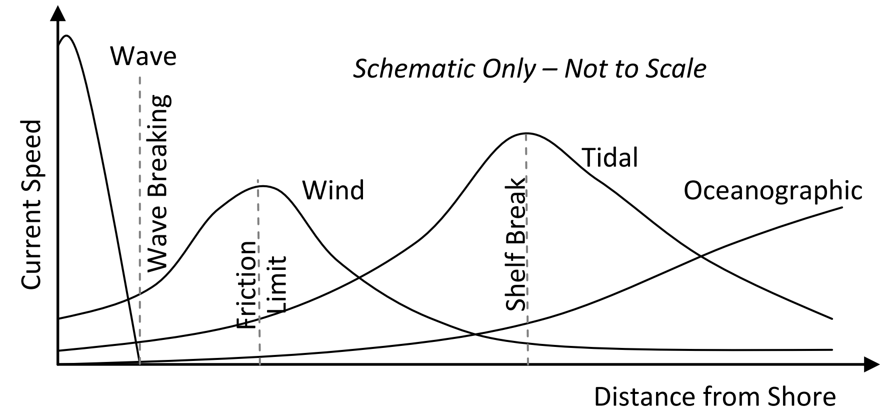



**Figure 4-9: Schematic Spatial Distribution of Currents Excluding Density Driven Currents (Source: Damara WA 2010a)**

Regional currents have been examined using satellite imagery, boat based measurements, numerical models and short-term deployments of current meters (Forde 1985; Mills *et al.* 1986; Holloway & Nye 1985; Holloway 1995; Pearce & Pattiaratchi 1997; Pearce *et al.* 2003; Heyward *et al.* 2006; Brinkman *et al.* 2007; Pattiaratchi 2008). These investigations provide a general focus on surface currents, including tidal currents; the Leeuwin Current; internal waves and tides on the Northwest Shelf; circulation within Exmouth Gulf and the Dampier Archipelago; and weather system forcing, including eddy formation and influences of islands.

In the Pilbara, currents in the nearshore region are dominated by tidal currents, particularly in the east of the study area (Figure 4-10) with weaker contributions from the other forces. It is noted that the most extreme currents observed in the Pilbara are induced by extreme winds and the propagation of continental shelf waves during the passage of the occasional tropical cyclone (Pearce *et al.* 2003). Once in motion, currents can be strongly influenced by local bathymetry and the presence of islands, for example, increased currents through island passages and the formation of wakes in the lee of islands (Pearce *et al*. 2003).

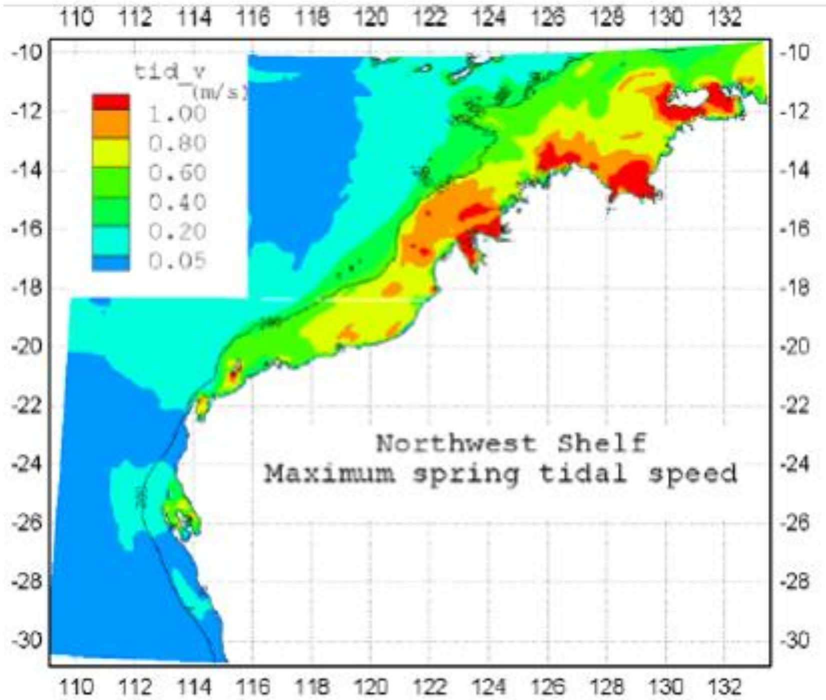



**Figure 4-10: Depth-Averaged Maximum Spring Tidal Speed (Li *et al.* 2008)**

### 4.2.5. Hydrology

Rivers and streams have a direct role in coastal evolution through flooding and sediment supply and storage, with influence on coastal landforms extending beyong the immediate river systems. The geomorphologic significance of rivers and streams is discussed in Section 3.4.1. The behaviour is highly dependent upon the catchment structure and hydrology, but also varies in time, responding to catchment saturation and the significance of preceding floods, with a general sequence of sediment release during extreme floods and sediment capture during lower flows.

River and creek flood character and capacity for sediment delivery to the coast are affected by the catchment structure. Distinction can be made between the three 'banjo-shaped' catchments of the Ashburton, Fortescue and De Grey Rivers, to the 'coastal' catchments of the Cane, Robe, Maitland, Harding, Sherlock, Yule and Turner Rivers. Many of the latter rivers and some coastal creeks have low gradients, and correspondingly low stream power to provide sediment delivery. In contrast, there is high sediment delivery from the 'banjo-shaped' catchments of the Ashburton, Fortescue and De Grey Rivers, which have relatively narrow coastal drainage paths and extensive upland areas separated by a topographic ridge. Although the coastal area generally receives higher rainfall, the upland area allows runoff concentration, with steeper stream gradients enhancing stream power (Figure 4-11).

Not all streams and rivers discharge directly into the ocean, with many releasing water and sediments into tidal flat basins and outwash plains. However, these systems are commently connected to the coast via tidal creeks and irregularly contribute sediment to the coast at times of flood. Discharge pathways are highly variable across the basins and outwash plains. Drainge pathways and areas of flood storage are impacted by engineering works such as levees, culverts and raising floor levels which affects flood risk. For example, the construction of the salt pond levees in the Onslow area (Gulf Holdings 1990; Onslow Salt 1995) reduced threat of runoff flooding, but has produced an alternative hazard associated with levee failure and has locally increased the level of runoff flooding outside the ponds.

Creek systems within the Pilbara region are often ephemeral, with locally significant incised channels draining ranges or escarpments in areas with rocky topography such as Dampier townsite, the Burrup Peninsula, Karratha and South Hedland. Flooding of these creeks typically occurs during high rainfall events. The coastal catchment structure can be complex with fronting dune or bar breakouts and flood basins. The local creek catchments are considered in studies of drainage for townsite expansion and consideration of flood risk for towns and future infrastructure projects (Aquaterra 2004; FMG 2004; GHD 2010a; JDA 2010a, b; URS 2010; GHD 2011; JDA *et al.* 2011a, b).

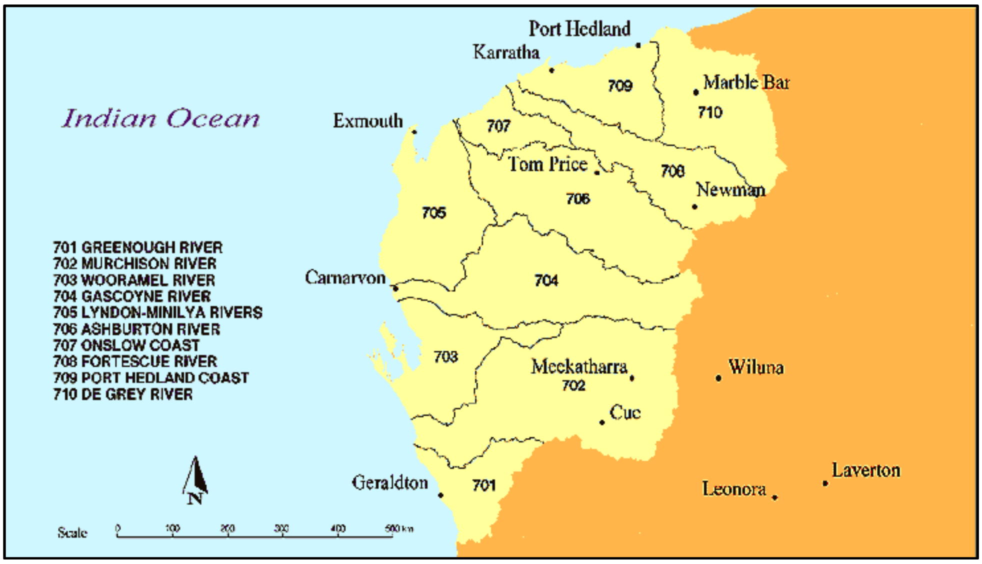



**Figure 4-11: River Catchments**
**(Source: Department of Water)**

The influence of rivers and creeks varies along the Pilbara coast in terms of flooding potential and influence on the sediment budget, and is considered a locally significant factor for all three of the Areas of Planning Interest (Section 6). The low-lying nature of most the Areas of Planning Interest, makes the coast potentially susceptible to flooding hazards from storm surge, runoff flooding or tsunami. Most flood studies require joint consideration of potential storm surge inundation. Flood studies and floodplain mapping have been revised recently for Karratha (GHD 2010a; JDA *et al.* 2011a, b) and Port Hedland (GHD 2011; JDA 2010b; Cardno 2011) for townsite expansion, with additional studies conducted for resource projects and port facilities (e.g. FMG 2004; URS 2010; BHP Billiton 2011). The transferral of flood and inundation hazard should be considered when designing any engineering works in these low-lying areas.

The Ashburton and De Grey Rivers have the highest potential river flow and provide the highest order of magnitude of terrestrial sediments to the coast (Table 4-5). This is a significantly smaller contribution than the Fitzroy and Ord Rivers in northern Australia. The values presented in Table 4-5 are mean annual estimates with significant inter-annual fluctuations and do not represent the potential carrying capacity during flood events (BoM 1998; NLWRA 2001; Li *et al.* 2008). An example of a recent flood was TC Monty which crossed the coast near Mardie on 1 March 2004 with more than 200mm of accumulated rainfall over western and central Pilbara (BoM 2011). Although not the biggest flood event on record, TC Monty caused flooding of the Ashburton River; sections of the Northwest Coastal Highway to be eroded by the Robe River; overtopping of the Fortescue River bridge; removal of abutments on the Maitland River Bridge; and flows of 3.9m above the spillway at the Harding River dam (BoM 2011).

**Table 4-5: Major Rivers and Potential Sediment Supply**
**Rivers within the Study Area are Shaded and Smaller Rivers are Italicised**
**(Source: WRC 1999; Ruprecht & Ivanescu 2000; Li *et al.* 2008; Department of Water website)**

| DoW Catch-ment | Sediment Source | Catchment Area ($km^2$) | River Flow (GL/y) | Approximate Suspended Sediment Export to the Coast (kT/y) | Mean Annual River Outflow at the Mouth Q ($m^3/s$) | Mean River Sediment Concentration C ($kg/m^3$) |
|---|---|---|---|---|---|---|
| 809 | Ord | 85,213 | 9,448 | 600 | 300 | 0.063 |
| 802 | Fitzroy | 103,900 | 4,800 | 2,635 | 152 | 0.549 |
| 710 | De Grey | 54,752 | 1,480 | 17 | 46.9 | 0.0117 |
| *709* | *Ridley* | - | - | - | - | - |
| 709 | Turner | 4,555 | 241 | 6 | 7.6 | 0.023 |
| 709 | Yule | 10,845 | 428 | 9 | 13.6 | 0.02 |
| *709* | *Peawah* | - | - | - | - | - |
| 709 | Sherlock | 5,168 | 193 | 1 | 6.1 | 0.0063 |
| *709* | *George* | - | - | - | - | - |
| 709 | Harding (dammed) | 1,797 | 38 | - | - | - |
| *709* | *Nickol* | - | - | - | - | - |
| 709 | Maitland | 2,123 | 92 | 2 | 2.9 | 0.023 |
| *709* | *Yanyare* | - | - | - | - | - |
| 708 | Fortescue | 50,006 | 363 | 7 | 11.5 | 0.0205 |
| 707 | Robe | 7,487 | 53 | - | - | - |
| 707 | Cane | 4,472 | 62 | - | - | - |
| 706 | Ashburton | 78,420 | 1,353 | 28 | 42.8 | 0.021 |
| *705* | *Yannarie (Yanrey)* | - | - | - | - | - |
| 704 | Gascoyne | 78,548 | 1,117 | 26 | 35.4 | 0.023 |
| 702 | Murchison | 89,184 | 410 | 21 | 13 | 0.049 |
| 701 | Greenough | 12,568 | 44 | 28 | 1.4 | 0.63 |

Small coastal catchments fronted by coastal dunes, or salt-flat basins with tidal creeks intermittently blocked by sandbars, can be temporarily flooded by local streams and are likely to require different management considerations. Inundation of flood basins and dune breakouts can occur during a significant flood, with the location of breaching influenced by areas of historic breakouts, narrow dune width and human intervention. Artificial breaches in the dunes for beach access and any drainage or floodway diversions modify flood behaviour. Such localised changes occur too rapidly to be captured adequately in flood studies.

## 4.3. LOCAL MODIFICATIONS

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

Some factors to consider for local processes include (not exhaustive list): the effect of the inner shelf morphology and islands; the geologic framework of the coast; subtidal terraces and tidal flats; groundwater behaviour; river and stream systems; and the sediment supply to the coast.

## 4.4. COASTAL CHANGE

### 4.4.1. Coastal Change Concepts

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

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

1. At the largest (geological) scales, coastal change is dominated by eustasy (sea level movements), isostasy, tectonics, lithification and occasionally vulcanology (van de Plassche 1986). These processes determine the presence of rock, and through movement of relative sea level, may relate to large movements of the coast;
2. At medium (geomorphic) scales, coastal evolution is determined by the production of mobile sediments, transfer via metocean forcing and accumulation in zones of relative shelter associated with the geologic framework of the coast. This suggests simulation of coastal change using sediment budgets tied to identification of large-scale sources, transport paths and sinks (Komar 1996; Rosati 2005) prompting the concept of equilibrium coastal alignment (van Rijn 1998);

3. Over short (planning) scales, large scale sinks and sources of material may be considered constant and shoreline fluctuations caused by storm erosion-recovery cycles may be considered almost in balance. Coastal change may be described largely by alongshore sediment transport and its variability, including spatial variation developed through changes in coastal aspect, and year-to-year metocean variations;
4. Over very short (coastal management) scales, dramatic coastal change occurs in response to weather cycles. This is most commonly represented as cross-shore transport associated with storm events and subsequent recovery during lower energy conditions (van der Meer 1988).

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

### 4.4.2. Coastal Change on the Pilbara Coast

**General Behaviour**

The prevailing coastal character of the Pilbara is its inherited terrain, with extremely variable sediment availably along the coast. More mobile sediments are intermittently delivered to the coast by numerous rivers and flowing streams, the largest being the Ashburton, Fortescue and De Grey Rivers. Not all streams and rivers discharge directly into the ocean, with many releasing water and sediments into tidal flat basins. However, these systems are connected to the coast via tidal creeks and irregularly contribute sediment to the coast at times of flood. The inherited character of the coast refers to the widespread presence of igneous rock and sedimentary features which sit relative to rock in such a manner that they are not directly responsive to present-day environmental forcing. Instead, these features have typically formed in response to historic conditions, often several thousand years before present, and are subsequently evolving gradually, but are resistant to moderate environmental conditions. Change largely occurs during extreme environmental conditions, and consequently there is a potential ‘tipping point’ response to climate change (Figure 4-12).

Active, inherited and fixed coastal components may all be present on a single section of coast, as illustrated by a perched dune above a rock scarp, fronted by an active beach (Figure 4-13).

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

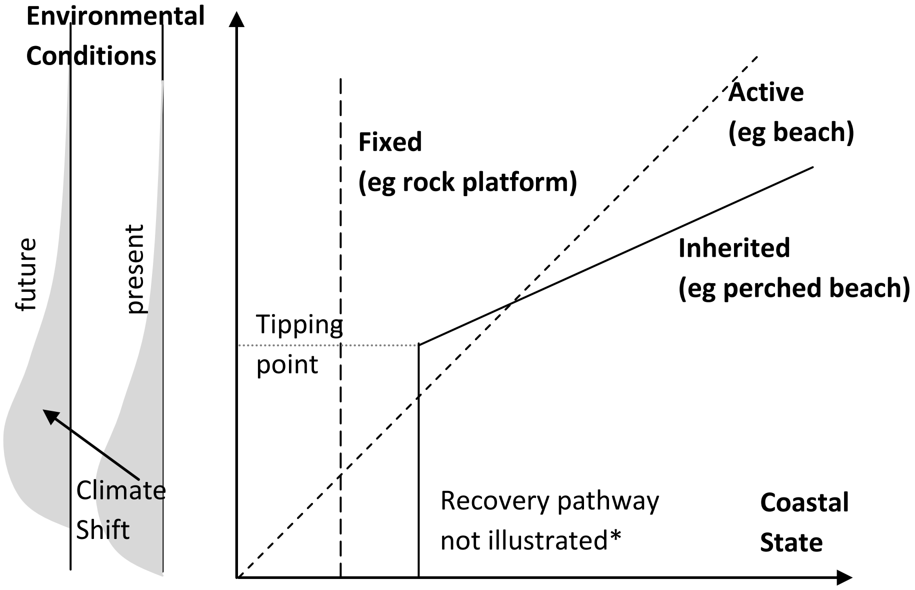



**Figure 4-12: Active, Inherited and Fixed Coast Response to Environmental Conditions (Schematic Diagram only)**
**The influence of recovery is not illustrated in this diagram. For active systems, recovery may mitigate response, enabling gradual response to increasing environmental conditions.**

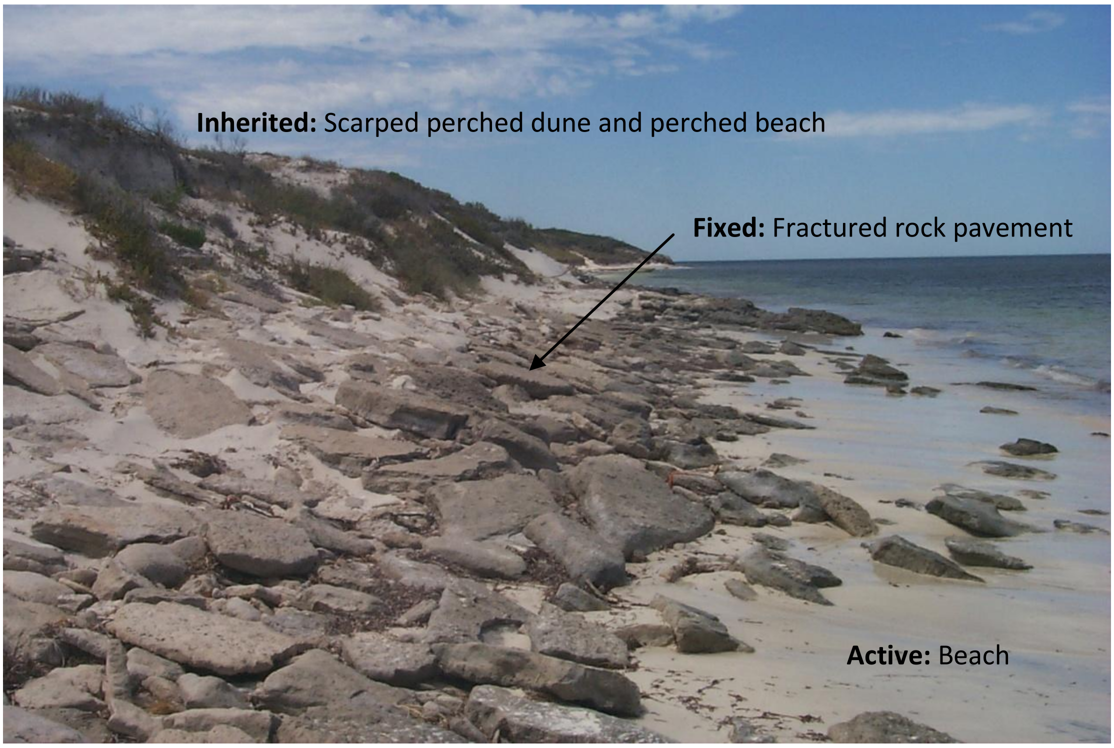



**Figure 4-13: Illustration of Active, Inherited and Fixed Coastal Components**

The inherited character of the Pilbara coast is significant for the calculation of coastal setbacks and coastal risk assessment. Anticipated coastal response requires consideration of the coastal type and level of inheritance, with variation throughout the Pilbara. Coastal setbacks incorporate calculation of:

- The relative response to moderate environmental conditions is likely to be low. Careful selection of the design event for **acute erosion** (S1) is required to capture the likely 100 year erosion event, with a 100-year ARI event likely to represent a 'miss' in the Pilbara. The traditional approach estimates the cross-shore horizontal extent of change, rather than looking at net or mean profile response, potentially exaggerating the ancitipated coastal response. Coastal response to extreme events should also include the longshore response due to wave-inducted currents, influence of rock control and connectivity. For coasts with dunes or spits, an assessment of dune storage and potential breaching during extreme events should be incorporated;
- Historic patterns of change are likely to be low (S2) as evolution is gradual, and may not reflect **potential change** associated with climate change tipping points. Determining historic change from aerial photography has limited scope for low-relief, rocky or engineered coasts due to vertical variation on the nearshore seabed and mudflats. Projecting potential future change from historic change requires consideration of rock control, landform connectivity, episodic sediment supply, future reliability of sediment supply, mechanics of erosion-recovery cycles, and the longshore variability in costal response;
- Geomorphic response to sea level rise rarely involves equilibrium profile shifting, therefore invalidating the use of the Bruun ratio. Allowance for **response to sea level rise** (S3) may need to be calculated on a case-by-case basis. Response should be estimated using a sediment budget approach incorporating the presence of underlying rock, the influence of obstacles (rock or manmade), future reliability of sediment supply and if structures will be maintained and adapted in future.

**Local Behaviour**

At a broad regional scale there is a paucity of detailed morphostratigraphic description and historical information describing metocean processes. Exceptions are research conducted in certain areas or related to certain projects as described in Section 4.2 above. The following general observations about coastal change and stability have been drawn from available information, site visits and interpretation of imagery. They are discussed at the scales of coastal change described above.

At a geological timescale features defining tertiary coastal compartments provide topographic control for the formation of unconsolidated landforms. This is significant where sediment is available, and the landforms have evolved over the past 10,000 years. Several sets of landform development are of particular interest.

1. The river systems directly connected to the ocean have contributed to coastal development through **delta building and floodplain development**; the Ashburton, Cane, Robe, Fortescue, Maitland, Harding, Sherlock, Yule, Turner and De Grey Rivers (Figure 1-3; Semeniuk 1993). The nature of their geologic inheritance, processes of change and deltaic landform responses differ for each river system. Significant floodplain development, including channel switching (avulsion) is currently apparent on the delta of the larger Ashburton, Fortescue and De Grey Rivers. Palaeochannels for the area are shown in Figure 4-14, providing an indication of potential avulsion. Apart from the large river systems are ephemeral creeks adjacent to rocky

topography, such as at Dampier, Karratha and South Hedland. These have small catchments with intermittently flowing streams that are locally important at times of high flood discharge and when they interact with coastal processes.

2. The Yannarie, Yanyare, Nickol, George, Peawah and Ridley River systems, and distributaries of the other river systems with direct connection to the coast, have contributed geologically to the formation of extensive **outwash plains** that grade to tidal flats along their seaward margins. These systems are connected to the coast via tidal creeks and irregularly contribute sediment to the coast at times of flood. The formation and maintenance of tidal flats, including their supratidal and subtidal components are of physical and biological significance. The significance of the former is due to their geographic extent within the region the latter due to their roles as essential life habitats.
3. **Barrier evolution** is continuing at present, albeit slowly, as sediment is moved along and across the shore. Phases of spit, chenier and dune activity associated with variation in the intensity and duration of metocean processes will continue to contribute to development of the dune ridge through the formation and destruction of foredunes, blowout activity and the migration of nested parabolic sand dunes. With the exception of the coast within and adjacent to deltas, many of the barriers overly coastal limestone and harder rocky topography – with the limestone an indication that they may be sediment deficient and have been subject to retreat during the late Holocene. At a similar geological timescale, the reef and headlands provide topographic control for the formation of sedimentary accumulation landforms, such as sand banks, spits, salients, cuspate forelands and tombolos.

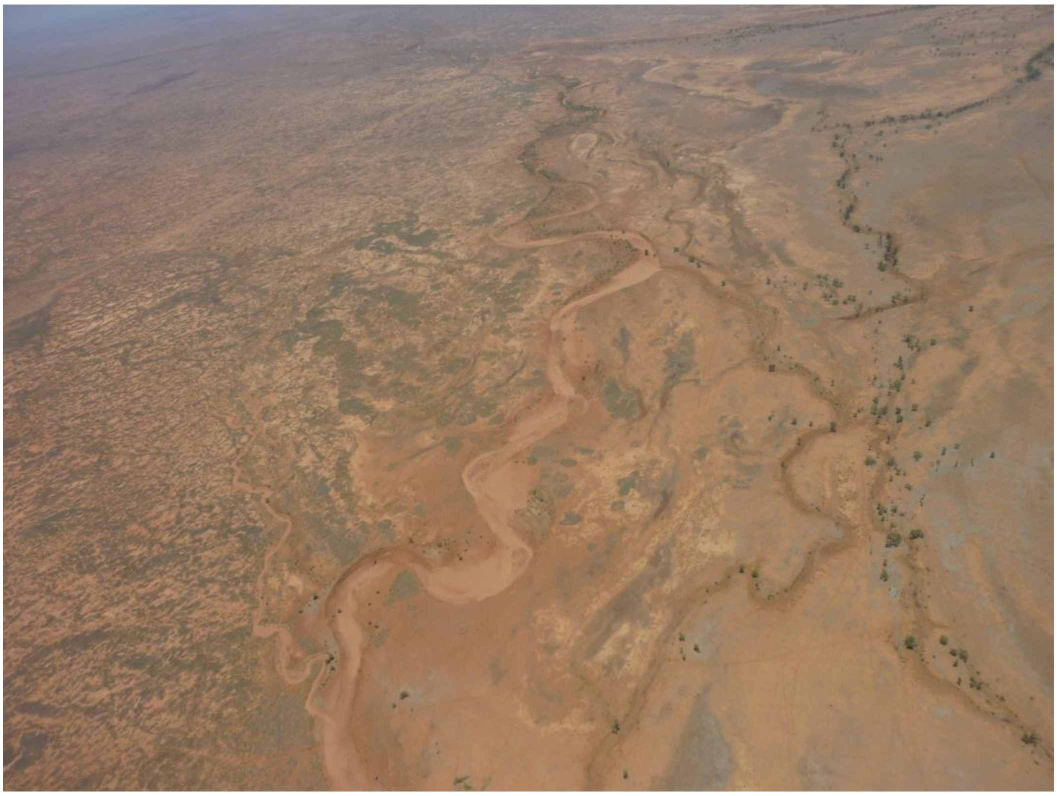


**Figure 4-14: River Distributaries and Palaeochannels**

Medium time scales are relevant to landform changes occurring over decades and centuries, including slow evolution of tidal creek networks on the mudflats skirting the shore (Semeniuk 1996); changes to landforms of the unconsolidated coasts such as alluvial landforms and dune barriers; and modification of cheniers, spits and storm bars by extreme events. The evolution of tidal creek networks responds to changes in mean sea level, sediment availability and connectivity with river systems (Section 3.4.2). Modification to alluvial landforms, dune formation and migration on the barrier is ultimately dependent on sediment supply from offshore and alongshore, and is associated with long-term variability in metocean processes, fluvial sediment supply and response to extreme events.

In some areas, the inner continental shelf morphology with its reefs, islands and sand shoals is critical to coastal stability and future evolution of accretionary landforms at the shore due to the combination of littoral sediment transport and rock-induced circulation patterns (DHI 2010; GEMS 2010a, b). The ramifications of this are that the future medium-term stability of the coast will potentially be affected by rates of onshore sediment supply, any updrift interference with the coastal sediment transport, or modification to the reef or headland controls, as well as by natural variability and change to metocean processes. In some places the intertidal accretionary forms, spits and bars, have closed bay mouths and impounded small coastal lagoons as has apparently occurred at Urala (Dodson & Eliot 2011). Extreme events, such as tropical cyclones and tsunami, have the potential to modify cheniers, spits and storm bars. This is indicated by washover features including sediment lobes landward of low-lying chenier ridges and storm bars as well as the orientation of long spits comprised of marine mollusc and oyster shells as well as silty sand. The landforms are tied to rocky headlands enclosing deep, NE facing enmbayments such as Nickol Bay. Spits and cheniers with recent wrack lines are also located up to 10km inland towards the landward limits of mudflats, as occurs near the old Balla Balla townsite. These are indicative of the reach of marine inundation due to storm surge and tsunami activity.

Local changes are also active over medium time scales as well as at sub-decadal scales, as any modification to sediment supply, or destabilisation and landward movement of spits or dunes, results in a loss of sand from the adjacent shore and exposure of rocky terrain, including pavement, beachrock ramps and platforms. Localised responses of accretionary landforms to metocean changes include gradual modification of spits and bars on subtidal and intertidal flats (including Hooley Creek spit), rapid response of coastal and alluvial landforms to flooding or extreme events and gradual (and probably incomplete) recovery, modifications to the distributary network of tidal creeks, bar opening and closing at the mouths of intermittent streams, and localised erosion and recovery of beaches and foredunes in the vicinity of headlands and rock outcrops along the shore. In areas where dunes have formed, changes in beach width largely correspond with dune and blowout activity, local drainage and modifications to downdrift sediment supply; examples occur at Onslow town beach and in the vicinity of Port Hedland including Cooke Point and Pretty Pool. Sandsheets have continued to form and rapidly migrate west to northwest (dependent on the local wind climate and topography), as has occurred at Tubridgi Point and areas supplied by fluvial sediments such as the area from Cape Cossigny to Cape Thouin.

At sub-decadal time scales modern metocean processes interact with the inherited geologic framework. The alongshore variation in coastal alignment, beach erosion and deposition, foredune formation, dune or spit development and mudflat response occurs as a result of interaction of the geologic framework and metocean processes with reaches of coast most susceptible to environmental change. This commonly occurs in close proximity to river systems, tidal creek mouths, shoreline salients and extensive rock outcrops. Localised estimation of shoreline change is necessary and should be linked to geophysical determination of the distribution and elevation of the underlying rocky terrain supporting the landforms and onshore structures, and the sediment availability in the inshore, mudflats and provided by the river systems.

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

### 4.4.3. Shoreline Movement

Naturally occurring movement of the shoreline has implications for proposed and existing coastal land use under the State Coastal Planning Policy SPP 2.6 (WAPC 2013). Shoreline change is typically described in terms of cross-shore and alongshore sediment movement (van Rijn 1998). The separation is fundamentally based upon geomorphic time scales, where cross-shore transport most commonly occurs under high frequency fluctuations associated with storms and water level variations; and nett alongshore transport is considered to represent slower changes, which may be evolutionary in nature. For example, from an analysis of 16 years of monthly data from Scarborough Beach, Clarke and Eliot (1983, 1987) attribute less than 5% of nett annual sediment movement to alongshore transport, despite being the major mechanism for long-term change.

Although the distinction between cross-shore and alongshore transport is convenient, it is not altogether accurate. Significant alongshore transport also may occur pulsationally and over short times frames, particularly where the inshore bathymetry is complex and there is periodic supply of sediments along and offshore associated with river flooding and through reef gaps and from inshore banks and bars, as it is on the Pilbara 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 along the backshore of sandy beaches. In the Pilbara, where sediment is actively moving inland from the shore, cheniers, spits and storm bars with washover features are formed. The effect of alongshore transport is apparent through the geological structure of the dune barriers and their landform patterns; the beach profile configuration in sheltered environments (Nordstrom 1992); spits and cheniers. The analysis applied to the Pilbara coast examined changes to beach, coastal dune, salient, spits, mudflat and alluvial components discernable from available aerial photography as well as ground reconnaissance. It provided an indication of the areas susceptible to change as well as the relative stability of landforms within each focal sediment cell. For example, in some places barriers are 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 three Areas of Planning Interest (Section 6). Vertical aerial photographs were examined for the earliest available record (1949-1968) to the most recent (2007-2009). Although this approach does not quantify shoreline, spit, dune and alluvial landform movement, comparison of the photographs indicates change in the shoreline position is localised to areas in the vicinity of river deltas, streams and tidal creek mouths; within the distributary networks of tidal creeks and rivers; between rock outcrops and on perched beaches; areas with spit and storm bar migration; corresponding to migration of salients; or in dunes downdrift of a fluvial sediment supply. In places, dunes migrate west-northwest; however, the photographic record is not sufficiently frequent to pinpoint the number of phases of accelerated migration and when each occurred.

In the context of long-term planning, evaluation of coastal stability requires consideration of potential changes over a range of time scales: from the short-term acute storm erosion, longer-term patterns of coastal evolution and impacts of projected climate change (Allan *et al*. 2003). These factors are considered within the State Coastal Planning Policy SPP 2.6 (WAPC 2013) through horizontal setback allowances for acute change, chronic change and sea level rise (S1, S2 and S3 respectively). The allowance for chronic change S2 is calculated as 100 times the assessed present longer-term rate of erosion.

Vegetation lines determined from vertical aerial photography are a commonly applied shoreline proxy nominated in SPP 2.6 as a measure for change on sandy shores that are not influenced by tropical cyclones. This measure may be limited along sections of the Pilbara coast, including areas with mangroves, rock, sub-tidal terraces, mudflats and outwash plains. For these shore types significant vertical variation of the nearshore seabed may occur without becoming apparent in the position of the adjacent vegetation or when assessed directly from above (Boak & Turner 2005). Consequently, vegetation line changes provide a poor proxy for coastal volumetric change, especially on low lying and rocky coasts. In this case, oblique aerial photography collected as part of WACoast (Gozzard 2012a) has been used in conjunction with vertical aerial photography to qualitatively describe historical change. The detection of vertical changes of mudflats and subtidal terraces is limited using this approach. The S2 component under SPP 2.6 *Schedule One* for these coasts may be evaluated through consideration of landform changes and the inter-relationships between landforms to develop an estimate of the overall sediment budget (Whitehouse *et al.* 2009a; JDA *et al.* 2011b Attachment 3).

Overall the historic record indicates the Pilbara shoreline is variable temporally and spatially. Areas of sediment accumulation are associated with fluvial systems, tidal creek networks and mudflats. Areas with greatest variability are on active river deltas; subtidal terraces, mudflats and outwash plains; adjacent to rocky outcrops; recurved spits and storm bars; and localised dune breakouts backed to landward by ephemeral creeks. Variability also occurs at salients, in the lee of islands and on perched beaches.

## 4.5. PROJECTED FUTURE CHANGE

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

As the predominant geomorphic character of the Pilbara coast can be described as inherited (see Section 4.4), implications of projected climate change and variability need to be considered relative to the environmental conditions responsible for the coastal configuration. Land-shaping conditions vary significantly between individual landform elements, but along the Pilbara coast, simple distinctions should be made between elements shaped by (i) modern or historic environmental conditions; and (ii) by prevailing or extreme conditions.

The combination of projecting modern trends, allowance for acute event response and estimation of change to the mean conditions is appropriate for landform elements shaped by prevailing modern processes. SPP 2.6 (WAPC 2013) suggests a methodology for the calculation of setback allowance on a sandy beach that incorporates these principles.

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

For those elements apparently shaped by extreme conditions, additional focus is required to define the likelihood of such extreme environmental conditions, and the potential change due to climate shifts. This approach is commonly applied to risk assessment of dune breaching (Dekker *et al*. 2005; Donnelly *et al.* 2006; Canizares & Irish 2008; Larson *et al*. 2009; Roelvink *et al.* 2009).

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

## 4.6. PILBARA COAST ENERGETICS OVERVIEW

Energetics potentially driving sediment transport across the Pilbara shelf are complex. The role of wave energy increases towards the shore and on the seaward side of ridges. Tidal currents change in direction and increase speed offshore, with localised areas of focusing where rock features (islands or ridges) provide restrictions. Connection between the shelf and inshore zones occurs intermittently through sand sheets or more extensive tidal structures such as the large ridges offshore from Port Hedland (Figure 6-47). The relative tendency for landward nearshore transport during ambient conditions is displayed by the formation of sand ribbons fronting low rocky cliffs, which are commonly crested by perched beach and dune systems (Figure 6-51).

Despite this complexity, the nature of nearshore sedimentary features, relative to the geological framework, indicates the tendency for a spatial sequence of environmental forcing (Figure 4-9, Table 4-6). The corresponding change to seabed formations demonstrates the offshore transition from wave to tidal dominance (Figure 6-47, Figure 6-48 and Figure 6-51). Changes in the advective and dispersive nature of seabed sediments at Port Hedland is further illustrated by the movement deposited dredge spoil, including landward movement of the spit adjacent to the shipping channel (GEMS 2010a). The spatial extent and speed of currents varies over time and with bathymetric structure. This determines that the zones are not fixed or wholly distinct, allowing direct connection, often for limited durations, between wind, wave and tidally formed sedimentary features. A spatial parallel occurs in locations where tidal currents may be high close to the shore, enabling interaction of forcing mechanisms. This occurs where deep water is close to shore, particularly along cliffs, or through exchange with tidal networks, including nearshore channels, tidal creeks and tidal flats.

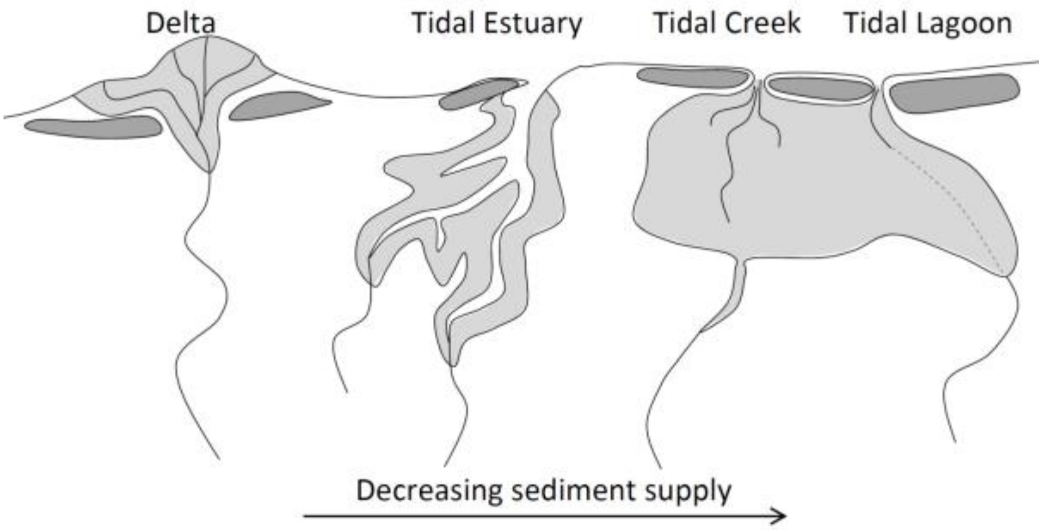
**Table 4-6: Indicative Spatial Variation of Current Mechanisms**

| Location | Driving Process | Primary Direction | Description |
|---|---|---|---|
| At the Shore | Waves | Alongshore | Radiation stress |
| Nearshore | Waves | Onshore | Orbital residual |
| Inshore | Winds | Alongshore | Deflected by surface gradient (surge) |
| Midshore | Winds | Variable | Inertial response |
| Inner Shelf | Tides | Basin determined | Controlled by bathymetry |
| Mid Shelf | Tides | Cross-shore | Peaks at top of shelf break |
| Outer Shelf | Oceanographic | Alongshore | Increases off shelf edge |

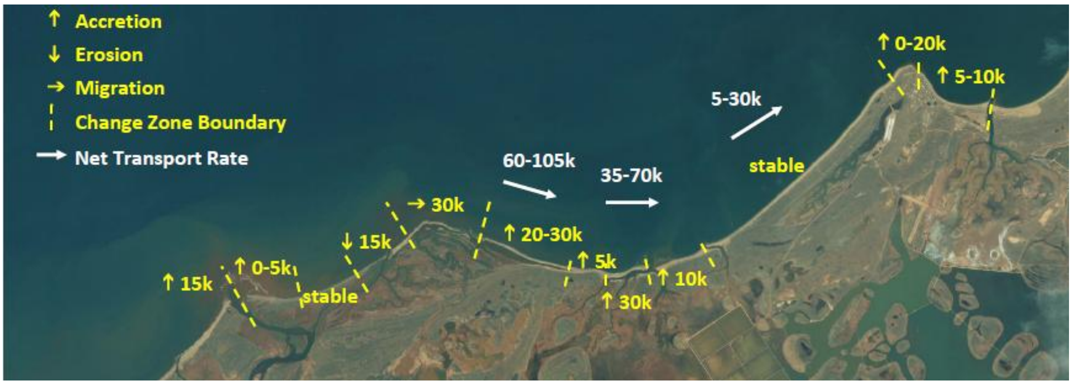
The onshore transport of material within the nearshore zone is an important factor in the formation and post-erosion recovery of coastal sedimentary features. The small scale of these features may imply that the delivery rate is constrained by the offshore sediment supply from tidal current dispersion.

Exchange between the coast and tidal networks provides a major pathway for sediments. This may be predominantly outgoing for deltas and incoming for estuary basins (Ryan *et al.* 2003). However, for the tidal flats prevalent along the Pilbara coast, rapid switching between erosion and accretion at the headward limit of tidal creeks indicates ability to either import or release sediment in response to changing conditions (Figure 3-4).

The mechanism of tidal flat adjustment has been argued as a major factor in the evolutionary behaviour across the Pilbara (Semeniuk 1994). When combined with the influence of proximity to sediment supply, the observed geomorphic progression (Figure 4-15) suggests that coastal wetlands and tidal flats may potentially have alternate pathways that either keep pace with sea level rise, or experience drowning, shifting a tidal flat towards a tidal lagoon.




(a) Conceptual relationship between supply and estuary form




(b) Notional sediment budget derived from surface features near Onslow

**Figure 4-15: Conceptual and Actual Progression of Estuarine Form in a Sediment Cell Extract from Eliot & Eliot (2013)**

Due to the presence of tidal flat systems along the majority of the Pilbara coast, the likely coastal response to sea level rise should incorporate a conceptual model of shore-estuary sediment transfer (Wang *et al.* 1998). The more widely applied conceptual model of shore-shelf sediment transfer may also be appropriate, although this should apparently incorporate tidal, wind and wave-driven transport. For areas where sediment delivery to the estuary is mainly marine, then the role of alongshore sediment transport is likely to be enhanced, compared to fluvial sources of sediment. The likely sediment deficit caused by sea level rise will therefore affect the sediment budget, with enhanced downdrift impacts within a sediment cell. This highlights the importance of considering change within a compartmentalised framework.

The patterns of behaviour described above provide a highly simplified explanation for the general manner in which the Pilbara coast operates. The importance of this pattern for the Pilbara coast is the ability for sand to be supplied to the coast, and the potential transfer from offshore sand sheets towards shore. The sand sheets themselves are largely relict from Holocene, and occasionally more modern deposits overlying Pleistocene limestone features (Semeniuk 1996).

Use of geomorphic frameworks when assessing likely coastal response to sea level rise in the Pilbara have either been qualitative (Semeniuk 1994) or applied to a relatively confined cell (JDA *et al.* 2011). However, the ability of the sediment budget approach to help explain the spatial variation of landforms and the observed patterns of coastal change suggest that geomorphic frameworks may be a valuable tool in the Pilbara, provided suitable refinement to incorporate tidal and floodplain effects. Key differences from the conceptual cross-shore balance model (Figure 4-16A) that have been interpreted from coastal observations and stratigraphic investigations in the Pilbara are the bi-directional role of onshore impoundment, the influence of coastal segmentation and the ephemeral nature of sediment storage associated with intermittent delivery of river sediments (Figure 4-16B).

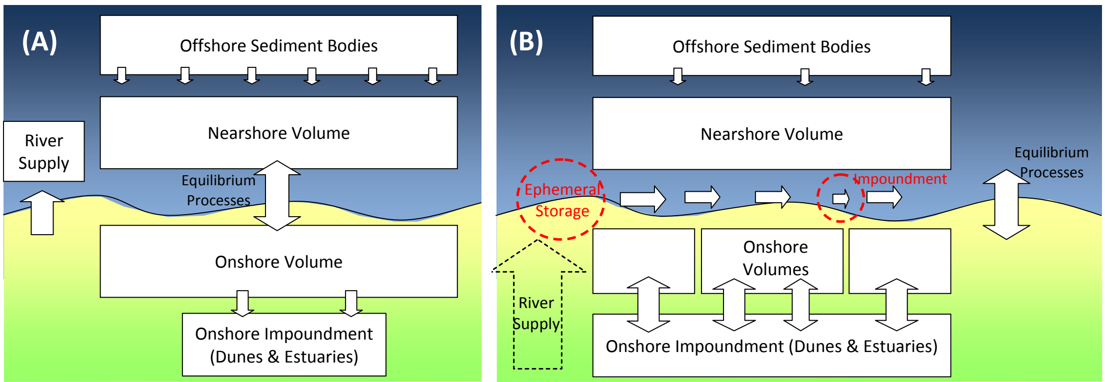



**Figure 4-16: Conceptual Models for Long-term Coastal Behaviour**
**(A) Dominance of Cross-Shore Balance; and (B) Behaviour Typical of the Pilbara Coast**

# 5. Land System Stability and Susceptibility to Change

The Pilbara coast comprises five primary, 14 secondary compartments and 34 tertiary compartments (Figure 1-2; Table 2-1), which progress from higher towards lower scale and degree of containment. In its western reaches the Study Area partly extends into a sixth primary compartment, the Eastern Gulf, and the secondary compartment of Giralia to Locker Point, which includes the Yannarie saltflats. In its eastern reaches the Study Area extends into a seventh primary compartment, Pindan, and the secondary compartment Cape Jaubert to Cape Villaret, which includes Eighty Mile beach. The vulnerability of the five complete primary compartments, including the Barrow, Dampier, Roebourne, De Grey and Wallal compartments (Figure 1-2), has previously been considered by Eliot *et al.* (2011a) for strategic planning, using a different approach based wholly on landform stability. They are not considered at this scale further in this report.

Tertiary compartments are considered at a land system scale appropriate to regional planning. Land systems for the 34 tertiary compartments have been identified, mapped (Appendix C) and their geology and geomorphology described (Appendix D). Further information on the land systems, including the associated landforms, is available from the relevant rangelands documents (Payne *et al.* 1988; Payne & Tille 1992; van Vreeswyk *et al.* 2004; Cotching 2005).

The Pilbara coast is considered in detail at a landform scale appropriate to local area planning for three Areas of Planning Interest at Onslow (Section 6.26.1), Karratha area (Section 6.3) and Port Hedland (Section 6.4). Landforms have been identified and mapped for 12 tertiary compartments spanning the Areas of Planning Interest, with two compartments for Onslow, nine for Karratha and one for Port Hedland (Figure 1-2; Table 2-1). The landform maps are included in Figure 6-11, Figure 6-18 to Figure 6-23 and Figure 6-50 in Section 6, extending 10km inland from the Landgate Mean High Water Mark. Each landform is described and attributed an instability rank (Table 6-5, Table 6-11 and Table 6-18), with maps demonstrating which landforms have low, moderate or high instability (Figure 6-12, Figure 6-24 to Figure 6-28 and Figure 6-58). These maps do not incorporate susceptibility or vulnerability and also neglect any landform connectivity.

Sediment cells are used as management units for landform scale assessments. The Pilbara Study Area includes four primary sediment cells and ten secondary sediment cells (Table 2-2; Figure 1-4). An incomplete coverage of 27 tertiary sediment cells was mapped, with 22 tertiary sediment cells selected to cover the key planning sites (Table 2-2; Figure 6-8; Figure 6-16; Figure 6-17 and Figure 6-45). The landforms for each tertiary sediment cell have been described at a finer spatial scale than that used to describe the tertiary compartments. Descriptions are presented for ten groups of cells within the three Areas of Planning Interest (Table 6-6; Table 6-12 and Table 6-17).

The groups of cells are those in the vicinity of:

- Onslow (Section 6.2)
    - Onslow - Tertiary Cells 1 to 3 from Rocky Point to Coolgra Point;
- Karratha area (Section 6.3)

  - Cape Preston – Tertiary Cells 4 to 7 from James Point to Pelican Point;
  - Dampier –Tertiary Cell 8 from Sharp Peak to Dampier;
  - Karratha – Tertiary Cells 9 to 11 from Nickol Bay W to Fields Creek;
  - Cleaverville and Anketell Coast – Tertiary Cells 12 to 15 from Fields Creek to Cape Lambert;
  - Point Samson – Tertiary Cells 16 to 18 from Cape Lambert to Butcher Inlet E;
- Port Hedland (Section 6.4)
  - Islands - Tertiary Cell 19 from Downes Island to Finucane;
  - Hedland Harbour - Tertiary Cell 20 from Finucane to Spoil Bank W;
  - Old Hedland - Tertiary Cell 21 from Spoil Bank W to Cooke Point; and
  - Beebingarra - Tertiary Cell 22 from Cooke Point to Petermarer Creek.

## 5.1. LAND SYSTEM SUSCEPTIBILITY & INSTABILITY

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

### 5.1.1. Susceptibility

The major natural structural features of the tertiary compartments were described (Appendix E) and ranked (Table 5-1) according to their likely susceptibility to change. Three (9%) of the 34 tertiary compartments have a low susceptibility; eighteen (53%) are moderately susceptible and 13 (38%) are highly susceptible. The implications of the groupings into low, moderate and high categories are summarised for each compartment in Appendix F.

Tertiary compartments have low susceptibility to change where the coast is protected by islands, with low wave and surge climates; has rock in the subtidal shoreface; is not an embayment facing NW to NE; has continuous bluffs, rocky coast or platforms; or is a high rocky coast with rock extending more than 5m above high tide. The areas with low susceptibility are the:

- Burrup Peninsula, including two compartments between West Intercourse Island and Cinders Road with rocky topography and sheltering by islands; and
- Rocky compartment between Cape Jaubert and Tryon Point.

Tertiary compartments considered moderately susceptible to change are exposed to moderate waves and moderate surge, or high waves and low surge or low surge and high waves; have patch reefs or intertidal/subtidal terraces in the subtidal shoreface; have lower elevation rock features such as a gently sloping rocky coast or near continuous intertidal platforms or perched beaches; have stationary/receded barriers, wide spits and cheniers or some outwash/deltaic plains. The moderately susceptible tertiary compartments are the following:

- Bare Sand Point to Hooley Creek with the active Ashburton River delta overlying a subtidal shoreface with extensive reef;
- Coolgra Point to Pelican Point with seven tertiary compartments with active deltas, inherited basins and outwash plains set within a bedrock framework;
- Cleaverville Creek to Cape Lambert with exposure to metocean forcing and unconsolidated sediments backed by a high rocky coast;

**Table 5-1: Susceptibility Rankings for Each Tertiary Compartment**

| Tertiary compartment | Inner Shelf Morphology | Subtidal Shoreface Structure | Intertidal Shore | Onshore Structures | Susceptibility Score | Susceptibility Ranking |
|---|---|---|---|---|---|---|
| Cape Jaubert to Tryon Point | 4 | 2 | 2 | 1 | 9 | L |
| Samphire Bore to Cape Jaubert | 3 | 2 | 3 | 3 | 11 | M |
| Eighty Mile Beach Caravan Park to Samphire Bore | 3 | 5 | 5 | 2 | 15 | H |
| Cooraidegel Well to Eighty Mile Beach Caravan Park | 2 | 2 | 4 | 3 | 11 | M |
| Shoonta Well to Cooraidegel Well | 2 | 2 | 4 | 3 | 11 | M |
| Cape Keraudren to Shoonta Well | 4 | 2 | 4 | 2 | 12 | M |
| Mulla Mulla Creek to Cape Keraudren | 3 | 2 | 4 | 3 | 12 | M |
| Condini Landing to Mulla Mulla Creek | 3 | 1 | 3 | 3 | 10 | M |
| Yan Well to Condini Landing | 3 | 5 | 5 | 4 | 17 | H |
| Wattle Well to Yan Well | 3 | 3 | 3 | 5 | 14 | M |
| Beebingarra Creek to Wattle Well | 2 | 4 | 5 | 5 | 16 | H |
| Downes Island to Beebingarra Creek | 3 | 2 | 4 | 5 | 14 | M |
| West Turner River to Downes Island | 3 | 3 | 4 | 5 | 15 | H |
| Cape Thouin to West Turner River | 4 | 4 | 5 | 5 | 18 | H |
| Cape Cossigny to Cape Thouin | 4 | 3 | 2 | 3 | 12 | M |
| Sherlock to Cape Cossigny | 3 | 4 | 5 | 5 | 17 | H |
| Cape Lambert to Sherlock | 3 | 4 | 4 | 4 | 15 | H |
| Cleaverville Creek to Cape Lambert | 4 | 3 | 4 | 1 | 12 | M |
| Karratha Back Beach to Cleaverville Creek | 3 | 3 | 5 | 5 | 16 | H |
| Cinders Road to Karratha Back Beach | 5 | 5 | 5 | 5 | 20 | H |
| Dolphin Island Point to Cinders Road | 3 | 2 | 3 | 1 | 9 | L |
| West Intercourse Island to Dolphin Island Point | 2 | 2 | 3 | 1 | 8 | L |
| Pelican Point to West Intercourse Island | 3 | 3 | 5 | 5 | 16 | H |
| Cape Preston to Pelican Point | 4 | 1 | 3 | 4 | 12 | M |
| James Point to Cape Preston | 3 | 3 | 4 | 4 | 14 | M |
| Mount Salt to James Point | 3 | 2 | 4 | 4 | 13 | M |
| Peter Creek to Mount Salt | 2 | 4 | 4 | 4 | 14 | M |
| Weld Island to Peter Creek | 2 | 2 | 5 | 4 | 13 | M |
| Yardie Landing to Weld Island | 1 | 2 | 5 | 5 | 13 | M |
| Coolgra Point to Yardie Landing | 3 | 2 | 4 | 2 | 11 | M |
| Hooley Creek to Coolgra Point | 4 | 2 | 4 | 5 | 15 | H |
| Bare Sand Point to Hooley Creek | 3 | 2 | 3 | 5 | 13 | M |
| Locker Point to Bare Sand Point | 3 | 3 | 5 | 4 | 15 | H |
| Hope Point to Locker Point | 4 | 4 | 5 | 4 | 17 | H |

- Cape Cossigny to Cape Thouin with exposure to metocean forcing; additionally unconsolidated sediments are perched on broad platforms backed by cheniers, dunes ridges and outwash plains of the Yule and West Yule Rivers;

- Downes Island to Beebingarra Creek with inherited basins set within a bedrock framework;
- Wattle Well to Yan Well with unconsolidated sediments from the active De Grey River mouth to the east overlying a bedrock framework;
- Condini Landing to Mulla Mulla Creek with low-lying outwash plains and wide cheniers overlying extensive subtidal and intertidal bedrock;
- Mulla Mulla Creek to Eighty Mile Beach Caravan Park with four tertiary compartments with beaches perched on extensive subtidal reef and discontinuous beach rock; and
- Samphire Bore to Cape Jaubert with a narrow sandy beach in a transition area from the low coastal plains of Eighty Mile Beach to an irregular coast dominated by rock outcrops and pindan soils.

The tracts of coast highly susceptible to change in the natural structure are commonly low-lying, containing the unconsolidated sediments of active deltas, inherited basins, outwash plains and narrow spits and cheniers, including:

- The two compartments from Hope Point to Bare Sand Point with outwash plains and deltaic plains of the Yannarie River, Chinty Creek and Ashburton River;
- Hooley Creek to Coolgra Point with deltaic plains of the Ashburton River that are susceptible to metocean forcing;
- Pelican Point to West Intercourse Island with the Yanyare and Maitland River deltas;
- The two compartments from Cinders Road to Cleaverville Creek, incorporating Karratha townsite, with the Nickol River and the mudflats joining Nickol Bay to Mermaid Sound. These compartments are susceptible to metocean forcing;
- The two compartments from Cape Lambert to Cape Cossigny with the Sherlock, East Harding, Harding and George Rivers;
- The two compartments from Cape Thouin to Downes Island with the outwash plains of the Yule and Turner Rivers;
- Beebingarra Creek to Wattle Well with the Ridley River and the deltaic plains of the De Grey;
- Yan Well to Condini Landing with the active De Grey River mouth; and
- The unconsolidated beaches and foredune plains of the Eighty Mile Beach Caravan Park to Samphire Bore with an absence of a bedrock framework.

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

Five complete primary compartments have been attributed a moderate or high susceptibility ranking based on the land systems present. The highly susceptible primary compartment (Roebourne) is comprised of low-lying land systems with active deltas, inherited basins and outwash plains.

Susceptibility of the sediment cells in the Areas of Planning Interest is addressed in Sections 6.2.4, 6.3.4 and 6.4.4. Across the three Areas of Planning Interest 22 tertiary cells were considered with two ranked as low susceptibility, seven as moderate susceptibility and 13 as high susceptibility. Many of the tertiary cells have a higher susceptibility ranking when considered at a finer spatial scale than tertiary compartments because the more susceptible natural structural features, such as narrow spits and cheniers or inherited basins comprise a higher proportion of the coast of interest.

**Table 5-2: Susceptibility for Compartments**
**Susceptibility and Instability Rankings should not be used independently**

| Primary Compartment | Rank | Secondary Compartment | Rank | Tertiary Compartment | Rank |
|---|---|---|---|---|---|
| PINDAN: Cape Jaubert to Swan Island (Extends beyond Study Area) | | Cape Jaubert to Cape Villaret (Extends beyond Study Area) | | Cape Jaubert to Tryon Point | L |
| WALLAL: Shoonta Well to Cape Jaubert | M | Eighty Mile Beach Caravan Park to Cape Jaubert | H | Samphire Bore to Cape Jaubert | M |
| | | | | Eighty Mile Beach Caravan Park to Samphire Bore | H |
| | | Shoonta Well to Eighty Mile Beach Caravan Park | M | Cooraidegel Well to Eighty Mile Beach Caravan Park | M |
| | | | | Shoonta Well to Cooraidegel Well | M |
| DE GREY: Beebingarra Creek to Shoonta Well | M | Condini Landing to Shoonta Well | M | Cape Keraudren to Shoonta Well | M |
| | | | | Mulla Mulla Creek to Cape Keraudren | M |
| | | | | Condini Landing to Mulla Mulla Creek | M |
| | | Yan Well to Condini Landing | H | Yan Well to Condini Landing | H |
| | | Beebingarra Creek to Yan Well | H | Wattle Well to Yan Well | M |
| | | | | Beebingarra Creek to Wattle Well | H |
| ROEBURNE: Cape Lambert to Beebingarra Creek | H | Cape Cossigny to Beebingarra Creek | H | Downes Island to Beebingarra Creek | M |
| | | | | West Turner River to Downes Island | H |
| | | | | Cape Thouin to West Turner River | H |
| | | | | Cape Cossigny to Cape Thouin | M |
| | | Cape Lambert to Cape Cossigny | H | Sherlock to Cape Cossigny | H |
| | | | | Cape Lambert to Sherlock | H |
| DAMPIER: James Point to Cape Lambert | M | Dolphin Island Point to Cape Lambert | M | Cleaverville Creek to Cape Lambert | M |
| | | | | Karratha Back Beach to Cleaverville Creek | H |
| | | | | Cinders Road to Karratha Back Beach | H |
| | | | | Dolphin Island Point to Cinders Road | L |
| | | West Intercourse Island to Dolphin Island Point | L | West Intercourse Island to Dolphin Island Point | L |
| | | Cape Preston to West Intercourse Island | H | Pelican Point to West Intercourse Island | H |
| | | | | Cape Preston to Pelican Point | M |
| | | James Point to Cape Preston | M | James Point to Cape Preston | M |
| BARROW: Locker Point to James Point | M | Peter Creek to James Point | M | Mount Salt to James Point | M |
| | | | | Peter Creek to Mount Salt | M |
| | | Coolgra Point to Peter Creek | M | Weld Island to Peter Creek | M |
| | | | | Yardie Landing to Weld Island | M |
| | | | | Coolgra Point to Yardie Landing | M |
| | | Locker Point to Coolgra Point | H | Hooley Creek to Coolgra Point | H |
| | | | | Bare Sand Point to Hooley Creek | M |
| | | | | Locker Point to Bare Sand Point | H |
| EASTERN GULF: Giralia to Locker Point (Extends beyond Study Area) | | Giralia to Locker Point (Extends beyond Study Area) | | Hope Point to Locker Point | H |

### 5.1.2. Instability

The present instability of landform features in the tertiary compartments was described (Appendix E) and the compartments ranked accordingly (Table 5-3). Difference between the rankings for susceptibility and instability assigned to the same compartment are notable and highlight the significance of long-term versus short-term change. Half of the tertiary compartments, 17 of the 34 (50%) have high instability, which is to say they are unstable compared to other compartments in the region. Four tertiary compartments (12%) have low instability and 13 (38%) have moderate instability. The implications of the groupings into low, moderate and high categories are summarised for each compartment in Appendix F.

Tertiary compartments are relatively stable and display low instability where the coast has: a limited amount of sediment stored inshore with sheltering by inshore reefs or rocky pavement; a nearly continuous rocky shoreface and hinterland; no rivers or only small coastal catchments; a high and wide frontal dune complex; a continuous lithified chenier ridge; or narrow saltflats. The areas with low instability are the:

- Burrup Peninsula, including two compartments between West Intercourse Island and Cinders Road with rocky topography and mostly rocky inshore substrate, no rivers or small coastal catchments, and few tidal creeks; and
- Rocky compartment between Cape Jaubert and Tryon Point with broad saltflats and some tidal creeks.

Combinations of some of the following factors indicate present levels of moderate landform instability: the inshore seabed contains approximately 50% bare sand; a river with a moderate sized inland catchment; river mouths discharge to a basin; a tidally dominated river delta with open mouth; the shore has one or two tidal creeks per 10km; the frontal dune complex is low and wide, moderately high and moderately wide or high and narrow or broad salt flats with tidal creeks and a vegetated margin. The moderately unstable tertiary compartments are:

- Locker Point to Bare Sand Point with sandy inshore areas and Chinty Creek and Ashburton River discharging to a basin with broad bare salt flats;
- Hooley Creek to Coolgra Point with a high and wide frontal dune complex broken by the tidal creeks of the large Ashburton River deltaic plains overlying rocky pavement;
- James Point to Pelican Point with two tertiary compartments overlying a rocky reef or pavement. The compartments have numerous tidal creeks, some of which link to the distributary streams of the Yanyare and Maitland Rivers, backed by saltflats and alluvial flats. The shore varies from rocky to sandy with discontinuous partially lithified chenier ridges and low, moderately wide frontal dunes;
- Cleaverville Creek to Cape Lambert with two embayments dominated by mudflats and tidal creeks within and overlying a bedrock framework;
- Cape Cossigny to Cape Thouin with a nearly continuous sandy shore perched on a broad platform, backed by a moderately high and wide frontal dune complex overlying an outwash plain of the Yule River;

- Downes Island to Beebingarra Creek with a bedrock framework broken by tidal creeks connected to the outwash plain and mudflats of the Turner River and Beebingarra, Petermarer and Tabba Tabba Creeks;
- Condini Landing to Mulla Mulla Creek with three tidal creeks, and associated mudflats with sediment supplied from the De Grey River, separated by subtidal and intertidal bedrock;
- Mulla Mulla Creek to Cape Keraudren with outwash plains merging with mudflats. Sand flats overlie subtidal reef with rocky headlands separating shores with tidal creeks and cheniers, spits and dune ridges.
- Cape Keraudren to Samphire Bore with four tertiary compartments characterised by the low coastal plains of Eighty Mile Beach. The compartments have sandy inshore sediments overlying patches of reef and discontinuous beach rock, with tidal flats increasing in width to the east. The narrow sandy beaches abut low and wide foredune and coastal dune ridges, backed to landward by mudflats and small tidal creeks; and
- Samphire Bore to Cape Jaubert with mainly sandy tidal flats narrowing to the north overlying a rock platform. Three sandstone ridges are impounded by broad expanses of mudflats with tidal creeks.

The highly unstable tracts of coast contain unconsolidated sediments and irregular shorelines along active deltas of moderate to large river catchments; inherited basins; outwash plains; broad mudflats with residual mounds, palaeochannels and tidal creeks; and shores fronted by low storm bars or low frontal dunes, including:

- Hope Point to Locker Point with the outwash plains of the Yannarie River with broad mudflats;
- Bare Sand Point to Hooley Creek with the active Ashburton River delta overlying rock pavement and platforms;
- Coolgra Point to James Point with five tertiary compartments with numerous tidal creeks, active deltas, inherited basins and outwash plains of the Cane, Robe and Fortescue Rivers set within a bedrock framework;
- Pelican Point to West Intercourse Island with the Yanyare and Maitland Rivers interacting with tidal creeks;
- The two compartments from Cinders Road to Cleaverville Creek, incorporating Karratha townsite, with the Nickol River and the mudflats joining Nickol Bay to Mermaid Sound with common tidal creeks and storm bars;
- The two compartments from Cape Lambert to Cape Cossigny with the outwash plains and lagoonal basins of the Sherlock, East Harding, Harding and George Rivers, incorporating mudflats and well developed tidal creeks;
- The two compartments from Cape Thouin to Downes Island with mudflats and tidal creeks draining the outwash plains of the Yule and Turner Rivers; and
- The three compartments from Beebingarra Creek to Condini Landing with the Ridley River, deltaic plains, palaeochannels, tidal creeks and active mouth of the large De Grey River.

**Table 5-3: Instability Rankings for Each Tertiary Compartment**

| Tertiary compartment | Inshore Substrate | Rivers or Tidal Creeks | Frontal Dune Complex or Tidal Flats (Shoreline) | Hinterland Topography or Supratidal Mudflats | Instability Score | Instability Ranking |
|---|---|---|---|---|---|---|
| Cape Jaubert to Tryon Point | 3 | 2 | 1 | 3 | 9 | L |
| Samphire Bore to Cape Jaubert | 3 | 3 | 2 | 3 | 11 | M |
| Eighty Mile Beach Caravan Park to Samphire Bore | 5 | 1 | 3 | 2 | 11 | M |
| Cooraidegel Well to Eighty Mile Beach Caravan Park | 4 | 1 | 3 | 3 | 11 | M |
| Shoonta Well to Cooraidegel Well | 4 | 1 | 3 | 3 | 11 | M |
| Cape Keraudren to Shoonta Well | 4 | 1 | 3 | 3 | 11 | M |
| Mulla Mulla Creek to Cape Keraudren | 4 | 2 | 3 | 4 | 13 | M |
| Condini Landing to Mulla Mulla Creek | 3 | 3 | 2 | 2 | 10 | M |
| Yan Well to Condini Landing | 5 | 5 | 4 | 5 | 19 | H |
| Wattle Well to Yan Well | 4 | 5 | 4 | 4 | 17 | H |
| Beebingarra Creek to Wattle Well | 4 | 4 | 4 | 5 | 17 | H |
| Downes Island to Beebingarra Creek | 3 | 3 | 3 | 5 | 14 | M |
| West Turner River to Downes Island | 4 | 3 | 4 | 5 | 16 | H |
| Cape Thouin to West Turner River | 4 | 4 | 2 | 5 | 15 | H |
| Cape Cossigny to Cape Thouin | 3 | 2 | 2 | 5 | 12 | M |
| Sherlock to Cape Cossigny | 4 | 5 | 4 | 5 | 18 | H |
| Cape Lambert to Sherlock | 4 | 4 | 2 | 5 | 15 | H |
| Cleaverville Creek to Cape Lambert | 2 | 4 | 3 | 2 | 11 | M |
| Karratha Back Beach to Cleaverville Creek | 4 | 5 | 4 | 5 | 18 | H |
| Cinders Road to Karratha Back Beach | 3 | 4 | 4 | 4 | 15 | H |
| Dolphin Island Point to Cinders Road | 2 | 1 | 2 | 1 | 6 | L |
| West Intercourse Island to Dolphin Island Point | 2 | 1 | 4 | 1 | 8 | L |
| Pelican Point to West Intercourse Island | 4 | 5 | 4 | 5 | 18 | H |
| Cape Preston to Pelican Point | 1 | 4 | 4 | 5 | 14 | M |
| James Point to Cape Preston | 3 | 5 | 4 | 2 | 14 | M |
| Mount Salt to James Point | 3 | 4 | 4 | 5 | 16 | H |
| Peter Creek to Mount Salt | 4 | 4 | 5 | 5 | 18 | H |
| Weld Island to Peter Creek | 3 | 5 | 4 | 5 | 17 | H |
| Yardie Landing to Weld Island | 4 | 5 | 5 | 5 | 19 | H |
| Coolgra Point to Yardie Landing | 3 | 4 | 3 | 5 | 15 | H |
| Hooley Creek to Coolgra Point | 3 | 4 | 1 | 5 | 13 | M |
| Bare Sand Point to Hooley Creek | 4 | 5 | 3 | 5 | 17 | H |
| Locker Point to Bare Sand Point | 4 | 2 | 1 | 5 | 12 | M |
| Hope Point to Locker Point | 4 | 5 | 5 | 5 | 19 | H |

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

**Table 5-4: Instability for Compartments**
**Susceptibility and Instability Rankings should not be used independently**

| Primary Compartment | Rank | Secondary Compartment | Rank | Tertiary Compartment | Rank |
|---|---|---|---|---|---|
| PINDAN: Cape Jaubert to Swan Island (Extends beyond Study Area) | | Cape Jaubert to Cape Villaret (Extends beyond Study Area) | | Cape Jaubert to Tryon Point | L |
| WALLAL: Shoonta Well to Cape Jaubert | M | Eighty Mile Beach Caravan Park to Cape Jaubert | M | Samphire Bore to Cape Jaubert | M |
| | | | | Eighty Mile Beach Caravan Park to Samphire Bore | M |
| | | Shoonta Well to Eighty Mile Beach Caravan Park | M | Cooraidegel Well to Eighty Mile Beach Caravan Park | M |
| | | | | Shoonta Well to Cooraidegel Well | M |
| DE GREY: Beebingarra Creek to Shoonta Well | H | Condini Landing to Shoonta Well | M | Cape Keraudren to Shoonta Well | M |
| | | | | Mulla Mulla Creek to Cape Keraudren | M |
| | | | | Condini Landing to Mulla Mulla Creek | M |
| | | Yan Well to Condini Landing | H | Yan Well to Condini Landing | H |
| | | Beebingarra Creek to Yan Well | H | Wattle Well to Yan Well | H |
| | | | | Beebingarra Creek to Wattle Well | H |
| ROEBURNE: Cape Lambert to Beebingarra Creek | H | Cape Cossigny to Beebingarra Creek | H | Downes Island to Beebingarra Creek | M |
| | | | | West Turner River to Downes Island | H |
| | | | | Cape Thouin to West Turner River | H |
| | | | | Cape Cossigny to Cape Thouin | M |
| | | Cape Lambert to Cape Cossigny | H | Sherlock to Cape Cossigny | H |
| | | | | Cape Lambert to Sherlock | H |
| DAMPIER: James Point to Cape Lambert | M | Dolphin Island Point to Cape Lambert | M | Cleaverville Creek to Cape Lambert | M |
| | | | | Karratha Back Beach to Cleaverville Creek | H |
| | | | | Cinders Road to Karratha Back Beach | H |
| | | | | Dolphin Island Point to Cinders Road | L |
| | | West Intercourse Island to Dolphin Island Point | L | West Intercourse Island to Dolphin Island Point | L |
| | | Cape Preston to West Intercourse Island | H | Pelican Point to West Intercourse Island | H |
| | | | | Cape Preston to Pelican Point | M |
| | | James Point to Cape Preston | M | James Point to Cape Preston | M |
| BARROW: Locker Point to James Point | H | Peter Creek to James Point | H | Mount Salt to James Point | H |
| | | | | Peter Creek to Mount Salt | H |
| | | Coolgra Point to Peter Creek | H | Weld Island to Peter Creek | H |
| | | | | Yardie Landing to Weld Island | H |
| | | | | Coolgra Point to Yardie Landing | H |
| | | Locker Point to Coolgra Point | M | Hooley Creek to Coolgra Point | M |
| | | | | Bare Sand Point to Hooley Creek | H |
| | | | | Locker Point to Bare Sand Point | M |
| EASTERN GULF: Giralia to Locker Point (Extends beyond Study Area) | | Giralia to Locker Point (Extends beyond Study Area) | | Hope Point to Locker Point | H |

Three of the complete primary compartments have been attributed high instability, with the other two attributed moderate instability, based on the landforms and land systems present. The three primary compartments of Barrow, Roebourne and De Grey have high instability due to the influence of rivers, streams and tidal creeks, with the compartments dominated by unconsolidated sediments, active deltas, inherited basins, outwash plains, deltaic plains, mudflats, palaeochannels and tidal creeks.

Instability of the sediment cells in the Areas of Planning Interest is addressed in Sections 6.2.4, 6.3.4 and 6.4.4. Across the three Areas of Planning Interest 22 tertiary cells were considered with four ranked as low instability, ten as moderate instability and eight as high instability. Many of the tertiary cells have a higher instability ranking when considered at a finer spatial scale than tertiary compartments because the more unstable landforms, such as floodplains and saltflats with residual mounds, palaeochannels and tidal creeks comprise a higher proportion of the coast of interest.

## 5.2. LAND SYSTEM VULNERABILITY

Vulnerability of the tertiary compartments was estimated by combining the overall rankings for susceptibility and instability to identify the likelihood of geomorphic change, grouped into five categories (Table 5-5; Figure 5-1; land systems maps in Appendix C). Descriptions of the main natural structural features and landform instability for each compartment are included in Appendix E. The majority of the tertiary compartments, 31 of the 34 (91%), have moderate, moderate-to-high or high vulnerability rankings. Ten compartments (29%) were each classified as moderate-to-high and high vulnerability categories. Eleven compartments (32%) have moderate vulnerability, no compartments (0%) have low-to-moderate vulnerability and three compartments (9%) have low vulnerability. The implications of the groupings into low, low-to-moderate, moderate and moderate-to-high categories are summarised for each compartment in Appendix F.

Tertiary compartments with low vulnerability are those with less susceptible natural structural features and low landform instability, as described in Section 5.1 above. The areas with low vulnerability, which have few constraints to coastal management at a tertiary compartment scale, are sections of rocky coast. The compartments ranked with low vulnerability include the:

- Burrup Peninsula, including two rocky compartments between West Intercourse Island and Cinders Road; and
- Rocky compartment between Cape Jaubert and Tryon Point with broad saltflats and some tidal creeks.

There are no compartments with low-to-moderate vulnerability.

Tertiary compartments of the Pilbara coast with moderate vulnerability have moderately susceptible natural structural features and moderate landform instability. These are areas with moderate constraints to coastal management at a tertiary compartment scale. These compartments are often located within a bedrock framework reducing the susceptibility compared to coasts without rock. The compartments may be associated with mudflats and irregular shorelines with one to two tidal creeks, perched sandy beaches or deltas, basins or outwash plains of *large creeks or moderate* sized river catchments. The compartments ranked with moderate vulnerability include:

- James Point to Pelican Point with two tertiary compartments with active deltas, inherited basins, outwash plains and numerous tidal creeks associated with the Yanyare and Maitland Rivers set within a bedrock framework;
- Cleaverville Creek to Cape Lambert with exposure to metocean forcing dominated by mudflats and tidal creeks within and overlying a bedrock framework;

- Cape Cossigny to Cape Thouin with exposure to metocean forcing, with a nearly continuous sandy shore, perched on broad platforms backed by cheniers, dune ridges and outwash plains of the Yule and West Yule Rivers;
- Downes Island to Beebingarra Creek with inherited basins, outwash plains and mudflats of the Turner River and three creeks set within a bedrock framework;
- Condini Landing to Mulla Mulla Creek with low-lying outwash plains, mudflats, three tidal creeks and wide cheniers overlying extensive subtidal and intertidal bedrock;
- Mulla Mulla Creek to Eighty Mile Beach Caravan Park with four tertiary compartments characterised by the low coastal plains of Eighty Mile Beach. There are narrow perched sandy beaches abutting tidal flats and low and wide foredune ridges, backed to landward by mudflats and small tidal creeks.
- Samphire Bore to Cape Jaubert with a narrow sandy beach, mainly sandy tidal flats narrowing to the north overlying a rock platform. Three sandstone ridges are impounded by broad expanses of mudflats with tidal creeks.

The tertiary compartments with moderate-to-high vulnerability are those with highly susceptible natural structural features or high landform instability. These are areas where coastal processes are likely to provide significant constraints to coastal management at a tertiary compartment scale. Nine of the ten compartments are associated with the active river deltas, deltaic plains, outwash plains, palaeochannels, tidal creeks and active mouths of *moderate to large* river catchments within a bedrock framework. These compartments are often susceptible to metocean forcing. The tidal creeks are likely to be connected to distributaries of rivers. These compartments are:

- Locker Point to Coolgra Point with three compartments associated with Chinty Creek and the Ashburton River
- Coolgra Point to James Point with five tertiary compartments associated with the Cane, Robe and Fortescue Rivers; and
- Wattle Well to Yan Well on the active De Grey delta, including a significant palaeochannels.

The unconsolidated beaches and foredune plains of the coast from Eighty Mile Beach Caravan Park to Samphire Bore, with an absence of a bedrock framework, is the only compartment with moderate-to-high vulnerability not directly associated with rivers.

Tertiary compartments with high vulnerability are those with highly susceptible natural structural features and high landform instability. These are areas subject to major constraints to coastal management at a tertiary compartment scale. The compartments are associated with active river deltas, deltaic plains, outwash plains, palaeochannels, tidal creeks and active mouths of *larger or numerous* river catchments often susceptible to metocean forcing. Most of the tidal creeks in these compartments are directly connected to distributaries of rivers. These compartments are:

- Hope Point to Locker Point with outwash plains of the Yannarie River and broad bare saltflats;
- Pelican Point to West Intercourse Island with the Yanyare and Maitland Rivers interacting with tidal creeks;

- The two compartments from Cinders Road to Cleaverville Creek, incorporating Karratha townsite, with the Nickol River and the mudflats joining Nickol Bay to Mermaid Sound with common tidal creeks. These compartments are susceptible to metocean forcing;
- The two compartments from Cape Lambert to Cape Cossigny with the outwash plains of the Sherlock, East Harding, Harding and George Rivers;
- The two compartments from Cape Thouin to Downes Island with the outwash plains of the Yule and Turner Rivers;
- Beebingarra Creek to Wattle Well with the Ridley River and the deltaic plains of the De Grey; and
- Yan Well to Condini Landing with the active De Grey River mouth.

A summary of the five levels of vulnerability across primary, secondary and tertiary compartments is shown in Table 5-6. This table again indicates adjustment of the vulnerability rankings with the scale of investigation because the proportion of coast comprising susceptible natural structural features and/or particular unstable landforms changes with scale. A summary of the susceptibility, instability and vulnerability across primary, secondary and tertiary compartments is included in Table 5-7.

The five complete primary compartments have been attributed moderate to high vulnerability rankings based on the natural structural features and landform stability present (Figure 5-1). Roebourne has a high vulnerability due to active deltas, inherited basins, outwash plains and broad mudflats with moderate-to-high exposure to metocean forcing. De Grey and Barrow both have moderate-to-high vulnerability due to active and inherited deltas. Dampier has moderate vulnerability at a primary compartment scale due to outwash plains and mudflats in a bedrock framework. Wallal has moderate vulnerability due to a lower number of rivers, streams and tidal creeks than the other primary compartments.

Vulnerability of the sediment cells in the Areas of Planning Interest is addressed in Sections 6.2.4, 6.3.4 and 6.4.4. Across the three Areas of Planning Interest 22 tertiary cells were considered with one ranked as low vulnerability, four as low-to-moderate, four as moderate, five as moderate-to-high and eight as high vulnerability. Many of the cells have a higher vulnerability ranking when considered at a finer spatial scale than the tertiary compartments because features of relatively higher coastal risk often represent a higher proportion of the coast of interest. Features with higher coastal risk include susceptible natural structures, such as narrow spits and cheniers or inherited basins, and more unstable landforms, such as floodplains and saltflats with residual mounds, palaeochannels and tidal creeks.

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

| Tertiary compartment | Susceptibility Rank | Instability Rank | Vulnerability Rank |
|---|---|---|---|
| Cape Jaubert to Tryon Point | L | L | L |
| Samphire Bore to Cape Jaubert | M | M | M |
| Eighty Mile Beach Caravan Park to Samphire Bore | H | M | M-H |
| Cooraidegel Well to Eighty Mile Beach Caravan Park | M | M | M |
| Shoonta Well to Cooraidegel Well | M | M | M |
| Cape Keraudren to Shoonta Well | M | M | M |
| Mulla Mulla Creek to Cape Keraudren | M | M | M |
| Condini Landing to Mulla Mulla Creek | M | M | M |
| Yan Well to Condini Landing | H | H | H |
| Wattle Well to Yan Well | M | H | M-H |
| Beebingarra Creek to Wattle Well | H | H | H |
| Downes Island to Beebingarra Creek | M | M | M |
| West Turner River to Downes Island | H | H | H |
| Cape Thouin to West Turner River | H | H | H |
| Cape Cossigny to Cape Thouin | M | M | M |
| Sherlock to Cape Cossigny | H | H | H |
| Cape Lambert to Sherlock | H | H | H |
| Cleaverville Creek to Cape Lambert | M | M | M |
| Karratha Back Beach to Cleaverville Creek | H | H | H |
| Cinders Road to Karratha Back Beach | H | H | H |
| Dolphin Island Point to Cinders Road | L | L | L |
| West Intercourse Island to Dolphin Island Point | L | L | L |
| Pelican Point to West Intercourse Island | H | H | H |
| Cape Preston to Pelican Point | M | M | M |
| James Point to Cape Preston | M | M | M |
| Mount Salt to James Point | M | H | M-H |
| Peter Creek to Mount Salt | M | H | M-H |
| Weld Island to Peter Creek | M | H | M-H |
| Yardie Landing to Weld Island | M | H | M-H |
| Coolgra Point to Yardie Landing | M | H | M-H |
| Hooley Creek to Coolgra Point | H | M | M-H |
| Bare Sand Point to Hooley Creek | M | H | M-H |
| Locker Point to Bare Sand Point | H | M | M-H |
| Hope Point to Locker Point | H | H | H |

| Key | Vulnerability of environmental change | Implications for coastal management (see Table 2-12 for further description) |
|---|---|---|
| | Low | Coastal risk is unlikely to be a constraint to coastal management |
| | Low -to-moderate | Coastal risk may present a low constraint to coastal management |
| | Moderate | Coastal risk may present a moderate constraint to coastal management |
| | Moderate-to-high | Coastal risk is likely to be a significant constraint to coastal management |
| | High | Coastal risk is a highly significant constraint to coastal management |

## Table 5-6: Vulnerability for Compartments

| Primary Compartment | Rank | Secondary Compartment | Rank | Tertiary Compartment | Rank |
|---|---|---|---|---|---|
| PINDAN: Cape Jaubert to Swan Island (Extends beyond Study Area) | | Cape Jaubert to Cape Villaret (Extends beyond Study Area) | | Cape Jaubert to Tryon Point | L |
| WALLAL: Shoonta Well to Cape Jaubert | M | Eighty Mile Beach Caravan Park to Cape Jaubert | M-H | Samphire Bore to Cape Jaubert | M |
| | | | | Eighty Mile Beach Caravan Park to Samphire Bore | M-H |
| | | Shoonta Well to Eighty Mile Beach Caravan Park | M | Cooraidegel Well to Eighty Mile Beach Caravan Park | M |
| | | | | Shoonta Well to Cooraidegel Well | M |
| DE GREY: Beebingarra Creek to Shoonta Well | M-H | Condini Landing to Shoonta Well | M | Cape Keraudren to Shoonta Well | M |
| | | | | Mulla Mulla Creek to Cape Keraudren | M |
| | | | | Condini Landing to Mulla Mulla Creek | M |
| | | Yan Well to Condini Landing | H | Yan Well to Condini Landing | H |
| | | Beebingarra Creek to Yan Well | H | Wattle Well to Yan Well | M-H |
| | | | | Beebingarra Creek to Wattle Well | H |
| ROEBURNE: Cape Lambert to Beebingarra Creek | H | Cape Cossigny to Beebingarra Creek | H | Downes Island to Beebingarra Creek | M |
| | | | | West Turner River to Downes Island | H |
| | | | | Cape Thouin to West Turner River | H |
| | | | | Cape Cossigny to Cape Thouin | M |
| | | Cape Lambert to Cape Cossigny | H | Sherlock to Cape Cossigny | H |
| | | | | Cape Lambert to Sherlock | H |
| DAMPIER: James Point to Cape Lambert | M | Dolphin Island Point to Cape Lambert | M | Cleaverville Creek to Cape Lambert | M |
| | | | | Karratha Back Beach to Cleaverville Creek | H |
| | | | | Cinders Road to Karratha Back Beach | H |
| | | | | Dolphin Island Point to Cinders Road | L |
| | | West Intercourse Island to Dolphin Island Point | L | West Intercourse Island to Dolphin Island Point | L |
| | | Cape Preston to West Intercourse Island | H | Pelican Point to West Intercourse Island | H |
| | | | | Cape Preston to Pelican Point | M |
| | | James Point to Cape Preston | M | James Point to Cape Preston | M |
| BARROW: Locker Point to James Point | M-H | Peter Creek to James Point | M-H | Mount Salt to James Point | M-H |
| | | | | Peter Creek to Mount Salt | M-H |
| | | Coolgra Point to Peter Creek | M-H | Weld Island to Peter Creek | M-H |
| | | | | Yardie Landing to Weld Island | M-H |
| | | | | Coolgra Point to Yardie Landing | M-H |
| | | Locker Point to Coolgra Point | M-H | Hooley Creek to Coolgra Point | M-H |
| | | | | Bare Sand Point to Hooley Creek | M-H |
| | | | | Locker Point to Bare Sand Point | M-H |
| EASTERN GULF: Giralia to Locker Point (Extends beyond Study Area) | | Giralia to Locker Point (Extends beyond Study Area) | | Hope Point to Locker Point | H |

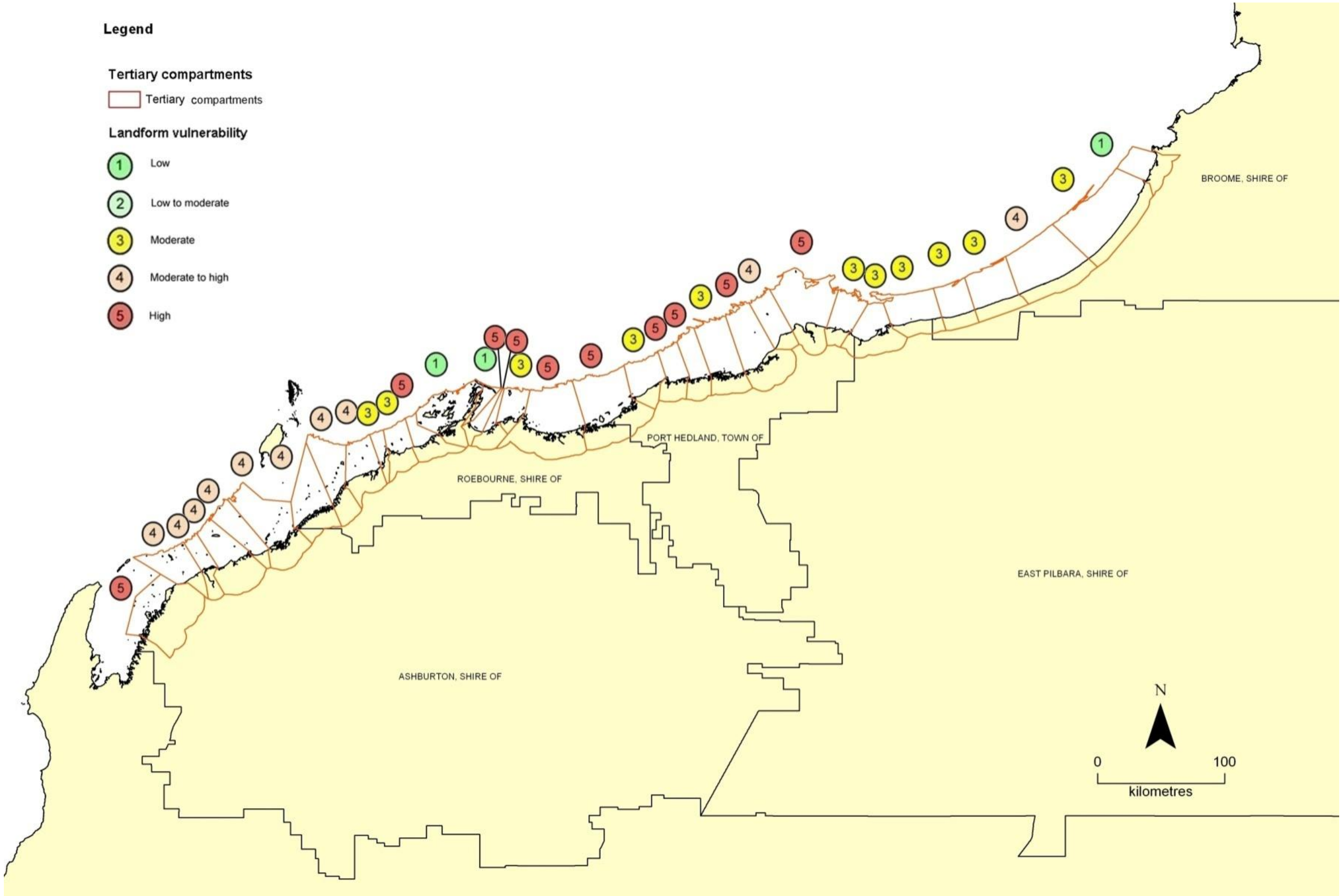



**Figure 5-1: Vulnerability Rankings for the Pilbara Coast**

**Table 5-7: Susceptibility, Instability and Vulnerability Rankings for Compartments**
**Primary and secondary compartment ranks were allocated from the mean ranking of the component tertiary compartments.**
**Note the component tertiary compartments are of unequal coastal extent.**

<table>
<tr><th rowspan="3">Tertiary Compartment</th><th colspan="3">Susceptibility<br>Compartment Rank</th><th colspan="3">Instability<br>Compartment Rank</th><th colspan="3">Vulnerability<br>Compartment Rank</th></tr>
<tr><th>1°</th><th>2°</th><th>3°</th><th>1°</th><th>2°</th><th>3°</th><th>1°</th><th>2°</th><th>3°</th></tr>
<tr><td>Cape Jaubert to Tryon Point</td><td></td><td></td><td>L</td><td></td><td></td><td>L</td><td></td><td></td><td>L</td></tr>
<tr><td>Samphire Bore to Cape Jaubert</td><td rowspan="4">M</td><td rowspan="2">H</td><td>M</td><td rowspan="4">M</td><td rowspan="2">M</td><td>M</td><td rowspan="4">M</td><td rowspan="2">M-H</td><td>M</td></tr>
<tr><td>Eighty Mile Beach Caravan Park to Samphire Bore</td><td>H</td><td>M</td><td>M-H</td></tr>
<tr><td>Cooraidegel Well to Eighty Mile Beach Caravan Park</td><td rowspan="2">M</td><td>M</td><td rowspan="2">M</td><td>M</td><td rowspan="2">M</td><td>M</td></tr>
<tr><td>Shoonta Well to Cooraidegel Well</td><td>M</td><td>M</td><td>M</td></tr>
<tr><td>Cape Keraudren to Shoonta Well</td><td rowspan="6">M</td><td rowspan="3">M</td><td>M</td><td rowspan="6">H</td><td rowspan="3">M</td><td>M</td><td rowspan="6">M-H</td><td rowspan="3">M</td><td>M</td></tr>
<tr><td>Mulla Mulla Creek to Cape Keraudren</td><td>M</td><td>M</td><td>M</td></tr>
<tr><td>Condini Landing to Mulla Mulla Creek</td><td>M</td><td>M</td><td>M</td></tr>
<tr><td>Yan Well to Condini Landing</td><td>H</td><td>H</td><td>H</td><td>H</td><td>H</td><td>H</td></tr>
<tr><td>Wattle Well to Yan Well</td><td rowspan="2">H</td><td>M</td><td rowspan="2">H</td><td>H</td><td rowspan="2">H</td><td>M-H</td></tr>
<tr><td>Beebingarra Creek to Wattle Well</td><td>H</td><td>H</td><td>H</td></tr>
<tr><td>Downes Island to Beebingarra Creek</td><td rowspan="6">H</td><td rowspan="4">H</td><td>M</td><td rowspan="6">H</td><td rowspan="4">H</td><td>M</td><td rowspan="6">H</td><td rowspan="4">H</td><td>M</td></tr>
<tr><td>West Turner River to Downes Island</td><td>H</td><td>H</td><td>H</td></tr>
<tr><td>Cape Thouin to West Turner River</td><td>H</td><td>H</td><td>H</td></tr>
<tr><td>Cape Cossigny to Cape Thouin</td><td>M</td><td>M</td><td>M</td></tr>
<tr><td>Sherlock to Cape Cossigny</td><td rowspan="2">H</td><td>H</td><td rowspan="2">H</td><td>H</td><td rowspan="2">H</td><td>H</td></tr>
<tr><td>Cape Lambert to Sherlock</td><td>H</td><td>H</td><td>H</td></tr>
<tr><td>Cleaverville Creek to Cape Lambert</td><td rowspan="8">M</td><td rowspan="4">M</td><td>M</td><td rowspan="8">M</td><td rowspan="4">M</td><td>M</td><td rowspan="8">M</td><td rowspan="4">M</td><td>M</td></tr>
<tr><td>Karratha Back Beach to Cleaverville Creek</td><td>H</td><td>H</td><td>H</td></tr>
<tr><td>Cinders Road to Karratha Back Beach</td><td>H</td><td>H</td><td>H</td></tr>
<tr><td>Dolphin Island Point to Cinders Road</td><td>L</td><td>L</td><td>L</td></tr>
<tr><td>West Intercourse Island to Dolphin Island Point</td><td>L</td><td>L</td><td>L</td><td>L</td><td>L</td><td>L</td></tr>
<tr><td>Pelican Point to West Intercourse Island</td><td rowspan="2">H</td><td>H</td><td rowspan="2">H</td><td>H</td><td rowspan="2">H</td><td>H</td></tr>
<tr><td>Cape Preston to Pelican Point</td><td>M</td><td>M</td><td>M</td></tr>
<tr><td>James Point to Cape Preston</td><td>M</td><td>M</td><td>M</td><td>M</td><td>M</td><td>M</td></tr>
<tr><td>Mount Salt to James Point</td><td rowspan="8">M</td><td rowspan="2">M</td><td>M</td><td rowspan="8">H</td><td rowspan="2">H</td><td>H</td><td rowspan="8">M-H</td><td rowspan="2">M-H</td><td>M-H</td></tr>
<tr><td>Peter Creek to Mount Salt</td><td>M</td><td>H</td><td>M-H</td></tr>
<tr><td>Weld Island to Peter Creek</td><td rowspan="3">M</td><td>M</td><td rowspan="3">H</td><td>H</td><td rowspan="3">M-H</td><td>M-H</td></tr>
<tr><td>Yardie Landing to Weld Island</td><td>M</td><td>H</td><td>M-H</td></tr>
<tr><td>Coolgra Point to Yardie Landing</td><td>M</td><td>H</td><td>M-H</td></tr>
<tr><td>Hooley Creek to Coolgra Point</td><td rowspan="3">H</td><td>H</td><td rowspan="3">M</td><td>M</td><td rowspan="3">M-H</td><td>M-H</td></tr>
<tr><td>Bare Sand Point to Hooley Creek</td><td>M</td><td>H</td><td>M-H</td></tr>
<tr><td>Locker Point to Bare Sand Point</td><td>H</td><td>M</td><td>M-H</td></tr>
<tr><td>Hope Point to Locker Point</td><td></td><td></td><td>H</td><td></td><td></td><td>H</td><td></td><td></td><td>H</td></tr>
</table>